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CALCULATIONS AND EXPERIMENTAL INVESTIGATIONS ON THE FEED-POWER REQUIREMENT OF AIRPLANES WITH BOUNDARY-LAYER CONTROL

By W. Krüger

TRANSLATION

"Rechnerische und experimentelle Untersuchung zur Frage des Förderleistungsbedarfes von Flugzeugen mit Grenzschichtbeeinflussung"

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CALCULATIONS AND EXPERIMENTAL INVESTIGATIONS ON THE FEED-POWER REQUIREMENT OF AIRPLANES WITH BOUNDARY-LAYER CONTROL*

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Abstract: Calculations and test results are given about the feed-power requirement of airplanes with boundary-layer control. Curves and formulas for the rough estimate of pressure-loss and feed-power requirement are set up for the investigated arrangements which differ structurally and aerodynamically. According to these results the feed power for three different designs is calculated at the end of the report.

Outline: A. Purpose of the investigations

B. General remarks on the feed-power requirement of airplanes with boundary-layer control

C. Feed-power requirement for three different arrangements for boundary-layer control which are structurally possible

I. Suction in the landing-flap region, blowing in the aileron region of the wing

II. Blowing over the entire span

III. Suction over the entire span

D. Results of measurements with respect to pressure-loss and power requirement

I. Suction in the flap region

II. Blowing over the entire span

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E. Comparison of the three arrangements according to an example

F. Summary and deductions

Bibliography

SYMBOLS AND DEFINITIONS

F_{ae} — aerodynamic wing area of reference for force and moment coefficients, meters^2

F — aerodynamic wing area of reference for the flow coefficient c_Q, meters^2

f — local flow cross section in the airplane, meters^2

$f_{s,B}$ — local flow cross section in the wing with suction or blowing arrangement, respectively, meters^2

f_H — local flow cross section in spar plane, meters^2

f_A — local flow cross section at the location of air expulsion, meters^2

f_R — greatest cross-sectional area of the fuselage, meters^2

f_G — flow cross section in the blower $\left(\frac{\pi}{4}(D^2 - d^2)\right)$, meters^2

f_{G_a} — blower cross section $\left(\frac{\pi}{4} D^2\right)$, meters^2

Q — total flow quantities (m^3/s)

c_Q — flow coefficient $\left(\frac{Q}{vF}\right)$

v — free-stream velocity (m/s)

w — local flow velocity in the interior of the airplane (m/s)

q — free-stream stagnation pressure (kg/m^2)

b — span of the wing, meters

b_R — spanwise extent of the fuselage, meters

y	coordinate in direction of span, meters
$y_{s,B}$	spanwise extent of one-half of the wing with suction or blowing, respectively, meters
$l_{i,a}$	inside or outside wing chord, meters
l_s	wing chord in the region of the wing with suction arrangement
l_B	wing chord in the region of the wing with blowing arrangement
$l_{mi_{s,B}}$	mean wing chord in the region of wing with suction or blowing, respectively
l_G	wing chord at the location of the blower, meters
D, d	outer diameter and hub diameter, respectively, of the blower, meters
z	height of flow passing through the throttling plane in the wing with suction, meters
D_{eff}	diameter of a circular cross section equivalent to the cross section of the interior ducting, meters
υ	hub ratio of the blower equal to d/D
s_S, s_B	slot width on the wing with suction or blowing, respectively, meters
d_{Pr}	profile thickness of the wing, meters
Λ	aspect ratio $\left(\frac{b^2}{F_{ae}}\right)$
λ	friction coefficient
K	roughness index (according to Hütte I), meters
ζ	drag coefficient for turn of ducting, throttling, sudden enlargement, diffusers
K_1	geometrical ratio $\left(\frac{z}{d_{Pr}}\right)$
K_2	geometrical ratio $\left(\frac{f_s}{l_s^2}\right)$

K_3	geometrical ratio $\left(\frac{f_B}{l_B{}^2}\right)$
Δp_{st}	difference of the static pressures in the external flow at entrance and exit (kg/m^2)
$c_{p_{st}}$	static-pressure coefficient $\left(\frac{\Delta p_{st}}{q}\right)$
G	weight of the airplane, kilograms
c_a	lift coefficient $\left(\frac{G}{qF_{ae}}\right)$
n	pressure loss coefficient $\left(\frac{\Delta p_v}{q c_Q{}^2}\right)$
N(PS) (German HP)	feed power
c_l	feed-power coefficient $\left(\frac{75\eta N}{\sqrt{\frac{G^3 2}{F_{ae}\rho}}}\right)\left(\frac{F_{ae}}{F}\right)$
η	blower efficiency
η_{Pr}	propeller efficiency

Subscripts:

B	wing with blowing arrangement
S	wing with suction arrangement

A. PURPOSE OF THE INVESTIGATIONS

The possibility of using boundary-layer control for production of high lift depends mainly on the question what structural, pressure, and flow requirements will be necessary to obtain a certain lift coefficient. The coefficients, c_Q and c_p, measured at the profile, alone do not yield sufficient information in this matter since in the flow through the airplane additional internal pressure losses originate, the magnitude of which depends on the feeding capacity and the flow conditions in the airplane. It does not seem possible to offer a solution of the problem of feed power requirement which would be valid for every design of the boundary-layer control apparatus. Thus only a few differing designs shall be investigated by calculations, which are partly supported by test results. The purpose of the calculations is only to give a survey of design requirements with consideration of the actual three-dimensional design relations of present aircraft types. The formulas for a rough estimate and the work sheets for computation presented in the sections C-I and C-II can give, for a preliminary design, quick and sufficient information on the influence of individual design features on pressure and feed-power requirement. Since it is the first and main purpose of this investigation to give information about the magnitude of the feed power, the problem of motive power for the feeding apparatus will not be further discussed.

B. GENERAL REMARKS ON THE FEED-POWER REQUIREMENT OF AIRPLANES WITH BOUNDARY-LAYER CONTROL

The mass of air used for boundary-layer control enters the airplane interior at the suction point S and leaves it at the blowing point B. This way, in the ideal case, no energy losses will occur in the interior of the airplane. The pressure jump required of the feeding apparatus in this case is composed of two parts, namely:

(1) The difference between the static pressures at suction and blowing point: $\Delta p_{st} = p_{st_B} - p_{st_S}$.

(2) The loss of kinetic energy at the exit: $\Delta p_A = \frac{\rho}{2} w_A^2$.

The first amount is, for a certain position of the suction and blowing point, dependent only on the flight stagnation pressure and on the angle of attack, therefore, $\Delta p_{st} = c_{p_{st}}(\alpha)\ q$, whereas the second amount is essentially influenced by the flow quantity and by the design of the exit.

Thus the feed power in the ideal case is:

$$N_i = Q(\Delta p_{st} + \Delta p_A) \quad (\text{m kg/s}) \tag{B1}$$

Actually total pressure losses occur in the flow through the airplane by friction and separations which are in good approximation proportional to the square of the internal flow velocity. Taking the efficiency of the feed apparatus into consideration, the actual power requirement then is:

$$N = \frac{1}{\eta} Q(\Delta p_{st} + \Delta p_A + \Delta p_v)$$

with Δp_A as well as Δp_V proportional to the local stagnation pressure $\frac{\rho}{2}\left(\frac{Q}{f}\right)^2$.

In the following calculation exit loss and internal pressure loss are referred to the stagnation pressure of reference $\frac{\rho}{2}\left(\frac{Q}{F}\right)^2$. The total pressure loss is then set up in the form:

$$\Delta p = n \frac{\rho}{2} \left(\frac{Q}{F}\right)^2$$

In this equation F represents the aerodynamic wing area of reference for the coefficient c_Q and n, a dimensionless pressure-loss coefficient which permits a direct comparison of the individual partial losses originated by the exit energy and by separations, friction, and directional changes in the flow through the wing.

Thus one obtains for the total pressure jump to be produced by the feeding apparatus and for the required feed performance

$$\left.\begin{aligned} \Delta p &= c_{p_{st}} q + n \frac{\rho}{2}\left(\frac{Q}{F}\right)^2 \qquad (\mathrm{kg/m^2}) \\ N &= \frac{1}{75\eta} Q\left[c_{p_{st}} q + n \frac{\rho}{2}\left(\frac{Q}{F}\right)^2\right] \quad (\mathrm{PS}) \end{aligned}\right\} \qquad \text{(B2)}$$

If one equates according to definition: $Q = c_Q \, v \, F$ and $q = \frac{G}{F_{ae} \, c_a}$, one can write the equations in the form:

$$\left.\begin{aligned} \Delta p &= \frac{G}{F_{ae} \, c_a}\left(c_{p_{st}} + n \, c_Q^{\,2}\right) \qquad (\mathrm{kg/m^2}) \\ N &= \frac{1}{75\eta} \sqrt{\frac{G^3 \, 2}{F_{ae} \, \rho}} \, \frac{F}{F_{ae}} \, c_l \qquad (\mathrm{PS}) \end{aligned}\right\} \qquad \text{(B3)}$$

where the feed-power coefficient $c_l = \dfrac{c_{p_{st}} \, c_Q + n \, c_Q^{\,3}}{c_a^{\,3/2}}$. The value

$c_{p_{st}}$ is not identical with the value c_p used in the publications so far because it takes only the static pressure in the external flow into consideration whereas c_p also contains the throttling losses at the entrance into the wing as they existed for the special test wing. $c_{p_{st}}$ can be determined from the test value c_p by forming for Q = constant the difference

$$c_{p_{st}} = \left(c_p - c_{p_{v_{duct}=0}}\right)_{Q=\text{constant}}$$

If c_p for $v_{duct} = 0$ is not measured, an estimate has to be made of the entrance losses.

The magnitude of the pressure-loss coefficient n depends on the kinetic energy at the exit of air fed, and on the aerodynamic merit of the flow ducts in the airplane interior and shall following be calculated for several different construction types. The power spent due to losses

$$N_v = \frac{1}{75\eta}\sqrt{\frac{G^3}{F_{ae}}\frac{2}{\rho}}\ \frac{F}{F_{ae}}\ \frac{n\ c_Q{}^3}{c_a{}^{3/2}}$$

increases with the third power of the coefficient c_Q. A reduction of the c_Q for a given c_a is therefore the more urgent the larger n; that is, the worse the flow conditions in the interior of the airplane and the higher the exit energy. For a given construction type (n) of the boundary-layer apparatus the power increases according to equation (B3) with the flight weight, the root of the surface loading, the feeding power coefficient c_l and the area ratio F/F_{ae}. In the case of suction or blowing over the entire span $F/F_{ae} \approx 1.0$. If one combines both kinds of boundary-layer control, suction and blowing, in one construction, there becomes, for $c_{Q_s} \approx c_{Q_B}$, $\frac{F}{F_{ae}} \approx 0.5$, since the same air quantity is used for suction and blowing. Thus this arrangement can be expected to be most favorable as concerns power requirements.

To give an idea of the ratio feeding power per total optimum propulsive efficiency the following comparison is made between the feed power and the gliding power at high speed:

<u>Feed power</u>: $N = \frac{1}{75\eta}\sqrt{\frac{G^3}{F_{ae}}\frac{2}{\rho}}\frac{F}{F_{ae}}\frac{c_{p_{st}} c_Q + n\, c_Q^{\,3}}{c_a^{\,3/2}}$

<u>Level flight power at high speed</u>: $N_s = \frac{1}{75\eta_{Pr}}\sqrt{\frac{G^3}{F_{ae}}\frac{2}{\rho}}\frac{c_{w_S}}{c_{a_S}^{\,3/2}}$ (subscript S = high speed)

$$\frac{N}{N_S} = \frac{\eta_{Pr}}{\eta}\frac{F}{F_{ae}}\frac{\left(c_{p_{st}} c_Q + n\, c_Q^{\,3}\right)\Big/ c_a^{\,3/2}}{c_{w_S}\Big/ c_{a_S}^{\,3/2}} \tag{B4}$$

From this equation one can determine for a project for which N_s, c_{w_s}, c_{a_s} are known, after estimating the efficiencies, what pressure-loss coefficient n is permissible for a desired $c_{a_{landing}}$ if N/N_s is limited to a certain magnitude. The connection between c_a and c_Q can be taken from measurements at the profile. Since the feeding power N for given structural conditions is, according to equation (B3), proportional to the feeding-power coefficient

$$c_l = \frac{c_{p_{st}} c_Q + n\, c_Q^{\,3}}{c_a^{\,3/2}}$$

there exists for each apparatus with respect to the feeding power an optimum c_a which can be obtained from the characteristic curve of the profile, if n is known. For instance in figures 1 to 3 $c_a = f(c_Q)$ and $c_l = f(c_a)$ is presented for the suction flap profiles 23012, 23015, and 23018 which were investigated in Göttingen(1). From the graphs one can see that c_l and c_Q/c_a have their minimum at about the same c_a-value. The c_a-value for which the feeding power coefficient becomes a minimum changes very little with the pressure loss coefficient n. The c_l-values become the more unfavorable in deviating from the optimum c_a, the larger n. Thus the improvement of c_a-values for aerodynamically bad flow conditions is a very costly one.

Because of the great importance of the pressure-loss coefficient n for the feed-power requirement of apparatus with boundary-layer control following three different arrangements that are structurally possible are investigated:

(1) Compound arrangement: Suction in the landing-flap region, blowing in the aileron region. Entire feeding apparatus in the wing.

(2) Blowing over the whole span. Entire feeding apparatus in the wing.

(3) Suction over the whole span. Entire feeding apparatus in the fuselage.

Either an axial blower or a jet apparatus is provided for as feeding apparatus. The calculations carried out in the sections C-I and C-II are supported by power and pressure-loss measurements on two wings of about 7.0 and 4.0 meters, respectively, semispan with a built-in axial blower of 300 millimeters outer diameter.

C-I. FEED-POWER REQUIREMENT FOR SUCTION IN THE LANDING-FLAP REGION AND BLOWING IN THE AILERON REGION OF THE WING (COMPOUND ARRANGEMENT)

Designations and arrangement of the apparatus can be taken from figure 4.

The flow cross sections at disposal in the wing interior are designated with f, the areas of wing with suction or blowing, for each case port and starboard together, with F.

The coefficient c_Q is referred to the entire area of the wing with suction; therefore $c_Q = \frac{Q}{v\,F_s} = c_{Q_s}$.

The total pressure loss arising in the flow through the wing is subdivided into the following parts:

(1) to (7): Internal losses

(1) Δp_E .. loss at the entrance into the suction flap slot.

(2) Δp_{Dr} loss caused by the throttling which is necessary for obtaining uniform distribution of feeding capacity

(3) Δp_{RS} friction loss in the wing with suction

(1) to (7): internal losses

(4) Δp_{KrS} turn of ducting - loss in the wing with suction

(5) Δp_D diffuser loss at the transition from the feeding apparatus to the wing with blowing

(6) Δp_{KrB} turn of ducting - loss in the wing with blowing

(7) Δp_{RB} friction loss in the wing with blowing

(8) Δp_A exit loss at the blow slot

The eight partial losses are compiled in table 1. The loss may be written in all cases: $\Delta p = \zeta \frac{\rho}{2} w^2$; w is the local flow velocity in the interior of the wing at the respective point. By using appropriate area and length ratios and taking the definition $Q = c_{Q_S} v F_S$ into consideration, all losses were referred to the free-stream stagnation pressure. Then the expressions to be found in the third column result for the partial losses. The dimensionless loss coefficients ζ contained therein were taken from the measurement (section D-I) on a wing of this special arrangement. The pressure-loss coefficients n for the various structural conditions in question can be taken from the curves and nomograms of the work sheet for computation 1. The sum of these partial pressure-loss coefficients is a measure for the magnitude of the total pressure loss in the flow through the wing since Δp is, according to equation (B3),

$$\Delta p = q(c_{pSt} + nc_Q^2) = c_{pSt}\, q + n \frac{\rho}{2} \left(\frac{Q}{F}\right)^2 .$$

The portions which correspond to the friction losses (n_{RS}, n_{RB}) are to a slight degree dependent on the absolute magnitude of the wing. However, since the friction losses are generally very small, this dependence can be neglected in first approximation and n can be assumed equal for all geometrically similar cases. In order to obtain a clear view of the influence of the area and length ratios on the separate pressure-loss coefficients, these latter are following compiled for three trapezoidal wings with a taper of 1:2 of the aspect ratio 5.0, 7.5, and 10.0. The main area and length ratios of the three wings can be taken from figure 5.

The following assumptions are made:

(1) Air duct through the wing according to arrangement I (fig. 4).

(2) Rear spar position at about 55 percent of the wing chord.

(3) Flap and aileron chord about 20 percent of the local wing chord.

(4) Area of wing with suction equal to area of wing with blowing $\left(c_{Q_s} = c_{Q_B}\right)$.

(5) Air feeding by an axial blower of the hub ratio $\upsilon = 0.5$.

(6) Blower entrance cross section lies approximately 25 percent of the spanwise extent of the suction wing toward the fuselage from the point of division between the suction and blowing ducts.

(7) Air duct channels in the wing interior with flat sheet covering.

(8) Blower shall just disappear in the profile contour (straak).

Under these assumptions one obtains from the work sheet for computation 1 for the given conditions the following pressure-loss coefficients:

No.	Partial losses	Pressure-loss coefficient n $\Lambda = 5$	$\Lambda = 7.5$	$\Lambda = 10$
1	n_E entrance loss $(s/l)_S = 0.02$ .03 .04	0.300×10^4 .130 .080	0.30×10^4 .13 .08	0.30×10^4 .13 .08
2	n_{Dr} throttling loss	.100	.100	.100
3	Friction loss suction wing n_{RS} $\left(\text{for } l_{mi_S} = 3.0 \text{ m}\right)$	.02	.04	.08
4	n_{KrS} turn loss suction wing	.05	.13	.22
5	n_D diffuser loss	.36	.96	1.84
6	n_{KrB} turn loss blow wing	.03	.05	.10
7	n_{RB} friction loss blow wing $\left(\text{for } l_{mi_B} = 2.0 \text{ m}\right)$	.05	.20	.44
8	n_A exit loss $(s/l)_B = 0.005$ .0075 .01	4.00 1.78 1.00	4.00 1.78 1.00	4.00 1.78 1.00

For customary slot dimensions of the suction slot of 3 percent of the chord, as they correspond for instance to the suction flap profiles measured in Göttingen, there results as total pressure-loss coefficient for various aspect ratios and blow slot widths:

		$\Lambda = 5$	$\Lambda = 7.5$	$\Lambda = 10$
n	$(s/l)_B = 0.005$	4.74×10^4	5.61×10^4	6.91×10^4
	.0075	2.52	3.39	4.69
	.010	1.74	2.61	3.91

The dependence $n = f(\Lambda, s/l_B)$ is presented in figure 6.

One can see from this diagram that n and therewith the power spent due to loss N_v is to a very high degree dependent on the slot-width ratio of the wing with blowing and on the aspect ratio of the wing. Besides the drawn-in curves for the total pressure-loss coefficient, the exit loss also is drawn separately (dashed-line curve). The share of the exit loss in the total loss increases with decreasing slot-width ratio $(s/l)_B$. The difference between n_{ges} and n_A indicates the magnitude of the internal pressure losses. This latter is largely dependent on the aspect ratio. For a customary blow slot of 0.75 percent of the wing chord the feeding-power requirement is almost twice as large for $\Lambda = 10$ as for $\Lambda = 5$. This tendency was to be expected since with increasing aspect ratio the disposable flow cross sections decrease and the length of the flow path increases. Therefore the friction, turn, and diffuser losses must increase strongly. A comparison of the partial losses (fig. 7) for customary slot widths $\left(\frac{s}{l}\right)_S = 0.03$ and $\left(\frac{s}{l}\right)_B = 0.0075$ shows that the exit and the diffuser loss form the largest part of the total loss, particularly so for high aspect ratios. It is therefore essential for obtaining small feeding powers to keep these two losses small.

The exit loss is for a given c_a dependent only on the exit slot width. It is inversely proportional to the square of the slot-width ratio. To keep it small that square would therefore have to be as large as possible. However, according to measurements on wings with blowing, the c_Q-requirement for a given c_a becomes in certain limits the smaller, the smaller $(s/l)_B$ (2), (3). If one wants to utilize this fact for the given arrangement, one has to reduce the ratio F_s/F_B, since $c_{Q_s} F_s$ must equal $c_{Q_B} F_B$. Thereby n also changes. The feeding power for given c_a is:

$$N \sim \frac{F_s}{F_{ae}} \left(c_{Q_s} c_{p_{st}} + n \, c_{Q_s}{}^3\right)$$

wherein

$$\frac{F_s}{F_{ae}} = f\left(\frac{c_{Q_s}}{c_{Q_B}}\right)_{c_a=\text{constant}}$$

and

$$n = f\left(\frac{F_s}{F_B}\right) = f\left(\frac{c_{Q_s}}{c_{Q_B}}\right)$$

Due to the complicated functional connections a general solution is hardly possible. It is more advantageous to perform numerically the calculation for each case with various slot width ratios and therewith various area ratios $\frac{F_s}{F_{ae}}$.

The diffuser loss for a given wing size depends essentially on the magnitude of the blower diameter. Since this loss is inversely proportional to the fourth power of the blower diameter, considerable gains in power can already be obtained by slightly raising the blower from the profile contour. In figure 8 the dependence $n = f\left(\frac{D}{l_G}\right)$ is plotted for $\Lambda = 5.0$, 7.5, and 10.0, and for the slot-width ratios 0.005, 0.0075, and 0.01. For instance for $\Lambda = 7.5$ and $\left(\frac{s}{l_B}\right) = 0.0075$ an increase of the ratio D/l_G from 0.1 to 0.14 reduces the power spent due to loss by one-half. Further increases no longer yield any essential improvement. For high-aspect ratios it is particularly important to select a large blower diameter. It shall be pointed out once more that the decrease of the pressure-loss coefficient n with increasing blow-slot width s/l_B, as shown in figure 8, by no means implies a corresponding decrease in power spent due to loss: it is known from experience that the c_Q-requirement of the part which is the wing with blowing for a certain c_a increases with growing blow slot width and that the power spent due to loss is proportional to the product $n\, c_Q{}^3$.

Approximate equation.- According to the calculation examples worked out so far, diffuser loss and exit loss form by far the major part of the total loss. Since these two depend mainly on $\frac{D}{l_G}$ and $\left(\frac{s}{l}\right)_B$, respectively, and the remaining losses, under the assumptions 1 to 7 made at the beginning of section C-I, on the aspect ratio, one can write for n:

$$n = n_A + n_D + n_E + n_{Dr} + Kr + R$$

$$= f_1\left(\frac{s}{l}\right)_B + f_2\left(\frac{D}{l_G}\Lambda\right) + f_3\left(\frac{s}{l}\right)_s + f_4(\Lambda)$$

For trapezoidal wings of the taper of 1:2 one can then obtain the following approximation for n:

$$n \approx \left(\frac{l}{s}\right)_B^2 + 4.9(\Lambda - 0.9)^2 \left(\frac{l_G}{D} - 4.8\right)^3 + 1.2\left(\frac{l}{s}\right)_s^2 + 10^2(\Lambda - 0.3)^2$$

range of validity is, according to assumptions 1 to 7, at the beginning of section C-I.

This approximate value for n can be substituted into the equations (B2), (B3), in order to determine the pressure loss and the power requirement.

The conditions become more favorable for a trapezoidal wing with rectangular center section and for the further case of a rear spar position < 55 percent, a taper ratio $> \frac{1}{2}$, $\frac{l_{Kl}}{l}$ or $\frac{l_Q}{l} < 0.2$, $F_s < F_B$, respectively, and of a hub ratio $\left(\frac{d}{D}\right) < 0.5$.

Since too large changes do not occur for moderate deviations from the assumed values, the equations are suitable for a first rough estimate. More accurate values can be obtained only with the aid of the work sheet for computation 1.

C-II. FEED POWER REQUIREMENT FOR BLOWING OVER THE ENTIRE SPAN

Designations and survey of the arrangement are shown in figure 9. The arrangement represents one of the many structural possibilities and has, accordingly, to be considered as a special case. Of course one could think of placing the blower or the jet apparatus, respectively, in the fuselage and to duct the air over turns into the wing. This solution was disregarded here because the fuselage offers only rarely sufficient space for the feeding apparatus.

The flow cross sections in the interior of the wing are designated by f, the area of the wing with blowing, port and starboard taken together, by F.

The coefficient c_Q is referred to the entire area of the wing with blowing; therefore, $c_Q = c_{Q_B} = \frac{Q}{vF_B}$.

The total pressure loss due to the flow through the wing is subdivided into the following portions:

(1) Δp_E loss at the suction point

(2) Δp_D diffuser loss behind the blower

(3) Δp_{Exp} loss by sudden enlargement

(4) Δp_A exit loss at the blow slot

Total pressure loss and power requirement can be calculated for this arrangement also according to equations (B2) and (B3), with $c_{p\ st} = \left(\frac{p_{st}}{q}\right)_B - \left(\frac{p_{st}}{q}\right)_S$. Since in this special arrangement the suction point is subjected to the full stagnation pressure and since, as is known from experience, $\left(\frac{p_{st}}{q}\right)_B \approx 0(2)$, $c_{p_{st}}$ becomes $c_{p_{st}} \approx -1.0$.

The four partial losses are compiled in table 2. The dimensionless loss coefficients were gained by comparison with a measurement on this arrangement. The results of this measurement are given in section D-II.

The pressure-loss coefficient n for the various design conditions can be taken from the curves of the work sheet for computation 2. For the total pressure-loss coefficient one obtains the expression:

$$n = n_{E+D+Exp} + n_A = \left(\frac{4}{\pi}\right)^2 \left[\frac{y}{l_{mi}} \left(\frac{l_{mi}}{l_G}\right)^2 \left(\frac{l_G}{D}\right)^2\right]^2 \left\{\zeta_E + \left(\frac{1}{1 - \upsilon^2}\right)^2 \left[\zeta_D + \left(\frac{1}{K_1}\right)^2 (\zeta - \zeta_D)\right]\right\} + \left(\frac{l}{s}\right)^2$$

One can see from this equation the dependence of the pressure-loss coefficient on the structural conditions:

$$n = f\left(\frac{y}{l_{mi}}, \frac{l_{mi}}{l_G}, \frac{l_G}{D}, \frac{l}{s}, \zeta_E, \zeta_D, \zeta, K_1, \upsilon\right)$$

For normal cases the hub ratio of the blower becomes approximately $\upsilon = 0.5$. The area ratio $K_1 = f_{spar}/f_G$ must not be made too large, in view of the fact that the diffuser has a rather good efficiency, since the lengths at disposal are small. For the wing investigated the area ratio was $K_1 \approx 1.25$. The loss coefficients can be assumed, according to the measurement results, $\zeta_E = 0.1$, $\zeta_D = 0.5$. The loss coefficient for the sudden enlargement at the exit from the spar plane lies, according to the measurements between $\zeta = 1.0$ to 1.5, varying with the throttling conditions (distribution of feeding capacity) in the wing; the higher values are to be used for the case that additional throttling vanes are built into the wing in order to obtain a uniform distribution of feeding capacity over the span. However, the distribution of the feeding capacity is even without additional throttlings quite satisfactory. It appears justified to assume $\zeta = 1.2$ if the blower lies at about the center of the semispan and $\zeta = 1.5$, if it is considerably displaced with respect to the center of the semispan.

Following the pressure-loss coefficients for the wings represented in figure 5 ($\Lambda = 5.0$, 7.5, and 10, $l_a/l_i = 1/2$) are calculated.

The blower shall lie at 40 percent of the distance $\frac{b - b_{fuselage}}{2}$ measured from the fuselage. For sudden enlargement $\zeta = 1.2$ will be used in the calculations:

Furthermore: $\zeta_E = 0.1$
$\zeta_D = 0.5$
$K_1 = 1.25$
$\upsilon = 0.5$

Λ	5.0	7.5	10.0
y/l_{mi}	2.32	3.58	4.73
l_{mi} l_G	.94	.94	.94

With these structural conditions one obtains for various aspect ratios, blower diameters, and slot widths the following pressure-loss coefficients:

$\frac{D}{l_G}$	$\frac{1}{10^4}n$	$\Lambda = 5$			$\Lambda = 7.5$			$\Lambda = 10.0$		
		$\frac{s}{l} = 0.005$	0.0075	0.010	0.005	0.0075	0.010	0.005	0.0075	0.010
	0.08	33.60	31.38	30.60	74.50	72.28	71.50	127.30	125.10	124.30
	.10	16.10	13.88	13.10	32.90	30.68	29.90	54.50	52.28	51.50
	.12	9.90	7.68	6.90	18.00	15.78	15.00	28.40	26.18	25.40
	.14	7.15	4.93	4.15	11.52	9.30	8.52	17.10	14.88	14.10
	.16	5.85	3.63	2.85	8.42	6.20	6.42	11.72	9.50	8.72
	.18	5.15	2.93	2.15	6.75	4.53	3.75	8.80	6.58	5.80
	.20	4.76	2.54	1.76	5.81	3.59	2.81	7.16	4.94	4.16
	.25	4.31	2.09	1.31	4.74	2.52	1.74	5.30	3.08	2.30

The graphs given in figure 10 show very clearly the immensely strong influence of the ratio D/l_G on the total pressure-loss coefficient, that is, on the power spent due to loss. Also for this type of installation the conditions grow worse with increasing aspect ratio. The larger Λ, the larger D/l_G has to be, if the power requirement is not to increase too much.

Rough estimate.- Similar to C-I, for this case also a rule-of-thumb formula shall be given; under the following assumptions:

$$\left.\begin{aligned} \zeta_E &= 0.1 \\ \zeta_D &= 0.5 \\ \zeta &= 1.2 \\ \upsilon &= 0.5 \\ K_1 &= \frac{f_H}{f_G} = 1.25 \end{aligned}\right\} \qquad \begin{gathered} \text{Trapezoidal wing } l_a/l_i = \tfrac{1}{2} \\ \text{Blower location at 40 percent of } \\ \frac{b - b_{fuselage}}{2} \end{gathered}$$

one can write for the total pressure-loss coefficient approximately:

$$n \approx 0.647\Lambda^2\left(\frac{l_{mi}}{l_G}\right)^4 \left(\frac{l_G}{D}\right)^4 + \left(\frac{l}{s}\right)^2$$

The equations (B2) and (B3) can be used for calculation of the pressure loss and of the power requirement. For rough estimates the approximative value for n is fully sufficient.

Result.- The construction type II "blowing over entire span" according to figure 9 shows for the case considered where the blower should disappear in the profile contour $\left(\frac{D}{l_G}\right) \approx 0.12$ that for equal c_Q essentially larger pressure losses result than for arrangement I. For $\left(\frac{s}{l}\right) = 0.0075$ and $\Lambda = 7.5$ the pressure-loss coefficient n of arrangement II equals about 4.7 times the one of arrangement I. The pressure loss $\Delta p = q\left(c_{p_{st}} + n\ c_Q^2\right)$ is, in spite of the worse aerodynamic conditions for arrangement II, not increased to the same degree as for arrangement I, because, according to the measurements made so far, the c_Q-requirement for equal c_a can be kept somewhat lower for blowing than for suction.

According to equation (B3) the power requirement is

$$N \sim \frac{F}{F_{ae}} \frac{c_{p_{st}} c_Q + n\, c_Q{}^3}{c_a{}^{3/2}}$$

the net power spent due to loss is therefore

$$N_v \sim \frac{F}{F_{ae}} \frac{n\, c_Q{}^3}{c_a{}^{3/2}}$$

If one as an approximation neglects the part covered by the fuselage one obtains for the powers spent due to loss for equal c_a:

Case I:

$$N_{vI} \sim \frac{1}{1 + \frac{c_{Q_s}}{c_{Q_B}}} n_I\, c_{Q_s}{}^3$$

Case II:

$$N_{vII} \sim 1\, n_{II}\, c_{Q_B}{}^3$$

$$\frac{N_{vII}}{N_{vI}} \approx \frac{n_{II}}{n_I} \left(\frac{c_{QB}}{c_{Q_s}}\right)^3 \left(1 + \frac{c_{Q_s}}{c_{Q_B}}\right)$$

In figure 11 the ratio of the powers spent due to loss N_vII/N_vI is presented as a function of c_{Q_B}/c_{Q_s} and $n\ II/n\ I$. Thus the capacity ratio c_{Q_B}/c_{Q_s} would have to be reduced to about 0.4 (for equal c_a, for instance for $n\ II/n\ I = 4.7$) in order to make the powers spent due to loss in the two cases of installation I and II equal. Ratios of such smallness have not been reached so far. According to the measurements taken so far, only for c_a-values which are larger than 3.5, blowing will yield a greater mass of air than suction. The feed-power requirement for arrangement II can be reduced essentially only by the use of large ratios "blower diameter/wing chord at the location of the blower." If one would succeed in installing simultaneously the feeding blowers into the existing nacelles of the motors of a multiengine airplane one would achieve many advantages at the same time. Namely:

(1) Large blower diameters and therewith smaller losses

(2) Eventual use of the feeding blower as blower for cooling in flight without suction

(3) No additional weight for motor of the feeding blower

(4) The feeding power is at disposal

The following circumstances constitute the difficulties of such a type of construction:

(1) Air duct from the blower to the wing should be as far as possible free of losses.

(2) The blower must operate at a larger rpm than the propeller. A gear transmission is necessary.

C-III. FEED-POWER REQUIREMENT FOR SUCTION OVER THE ENTIRE SPAN

The arrangement represented was investigated in figure 12 in the same way as arrangements I and II; for this arrangement the air quantity obtained by suction at the wing is fed by a feeding apparatus installed in the fuselage and is blown out in the rear part of the fuselage surface. Since the blower is installed in the fuselage and, besides, a considerable part of the fuselage volume must be used as air duct, storage space is lost. The apparatus is therefore hardly suitable for use in airplane construction (aside from special cases of test engines). Presentation of the calculation is therefore omitted. In section E the power requirement of the arrangement III for a special airplane as it results from the calculations omitted here is given for comparison with the arrangements I and II.

D-I. MEASUREMENT RESULTS ON PRESSURE LOSSES AND POWER REQUIREMENT. ARRANGEMENT I, COMPOUND ARRANGEMENT. "SUCTION IN THE FLAP REGION, BLOWING IN THE AILERON REGION"

A. Purpose of the Investigation

B. Model Description and Test Procedure

C. Test Results

A. Purpose of the Investigation

The connection between feeding quantity, pressure loss, and power requirement is to be established for a wing with boundary-layer control where suction of air is applied in the landing-flap region and blowing in the aileron region. Furthermore, it has to be investigated whether for the selected arrangement of the blower and the jet apparatus, respectively, a satisfactory distribution of the suction and blowing quantity along the span can be obtained.

B. Model Description - Test Procedure

The data for the construction of the test wing were taken from the dimensions of a wing with boundary-layer control for high lift production planned by the firm Arado - Flugzeugwerke, Brandenburg. The dimensions of the test wing can be seen from figure 13. The feeding of air was accomplished by a two-stage axial blower of 300 millimeters outer diameter, the characteristic of which can be seen from figure 14. (4). The blower was driven by an electromotor of 40 kilowatts power at 4000/minute with pendulum type of bearings over a blower (sic!) of the transmission ratio 1:2. For reasons of experimental technique an inclination of the blower shaft with respect to the rear spar plane by 7.5° was required as can be seen from figures 13 and 15. The main area and length ratios of the wing are as follows:

$$\left(\frac{s}{l}\right)_s = \begin{matrix} 0.018 \\ .032 \end{matrix} \text{ for } \eta_{Kl} = \begin{matrix} 48^\circ \\ 60^\circ \end{matrix} \qquad \left(\frac{l_{mi}}{l_o}\right)_B = 0.752$$

$$\left(\frac{s}{l}\right)_B = 0.008 \qquad \upsilon = \left(\frac{d}{D}\right)_G = 0.5$$

$$\left(\frac{d_{Pr}}{l}\right)_s = 0.18 \qquad F_s/F_B = 1.20$$

$K_1 = \frac{z_{mi}}{d_{Pr}} = 0.20$

$(y/l_{mi})_s = 1.35$

$l_{mi_s}/l_G = 1.00$

$D/l_G = 0.13$

$\left(\frac{y}{l_o}\right)_B = 1.52$

$F_s/l_{B_o}{}^2 = 1.36$

$K_2 = f_s/l^2 = 0.0235$

$K_3 = f_B/l^2 = 0.0210$

$\Lambda = \frac{b^2}{F} = 7.6$

$l_{s_{mi}} = 2.31$ m

$l_{B_{mi}} = 1.67$ m

For determination of the feeding capacity the velocity profiles in the suction flap slot were measured. The integration of the velocity over the span of the suction part of the wing and over the slot width yields the feeding capacity. The results of this measurement of capacity were in good agreement with a numerical determination of the feeding capacity from the mean static pressure in the wing with blowing and the blow slot area. In order to obtain a favorable distribution of the feeding capacity along the span of the suction part of the wing a throttling vane was arranged closely behind the suction slot (fig. 15); the height of the opening through which the flow passes could be regulated in such a manner that approximately equal quantities entered referred to a unit of span length. The pressure jump of the blower was measured with total pressure tubes which were distributed over the entrance and exit cross section. In order to determine the distribution of the feeding capacity on the wing with blowing the total pressure distribution in the exit jet was measured on the multiple-tubed manometer with the aid of a pressure rake; from the total pressure distribution the local velocity profile was calculated under the assumption that the static pressure in the free jet equals zero. The power at the motor shaft could be determined by measurement of the torque and the rpm. Friction power of shafts and gears were measured separately, with the blower disconnected.

C. Test Results

(1) The c_Q-distribution along the span of the suction part of the wing can be made approximately uniform with the aid of the throttling vane installed behind the suction flap slot. Even without this additional measure it is better than could be expected for the unfavorable installation. Figure 16 shows the course of $\frac{c_{Q_y}}{c_{Q_{mi}}}$ along the span of the wing with suction for the case "a" without additional throttling and for "b" with the most favorable throttling with respect to the distribution of the feeding capacity. The ratios pertinent to the most favorable distribution of feeding capacity $\left(\frac{z}{l}\right)_y$ are also plotted there. Therefore for this wing the free-stream cross section at disposal along the span of the suction part of the wing must be reduced to about one-half in order to make the c_Q-distribution uniform.

(2) The c_Q-distribution on the wing with blowing (fig. 17) shows very strong variations along the span, which are, however, caused by a faulty construction. The spaces between the minima correspond rather accurately to the rib spacing of the test wing. If one draws in a mean value - curve, there results for all investigated diffuser arrangements a slight increase of the c_Q-values toward the outside, which appears favorable with respect to stability. The ratio $\frac{s}{l}$ (slot width/wing chord) was not exactly the same, as can be seen from figure 17. According to the results of new tests the variations in the c_Q-distribution can to a great extent be eliminated if the ratio $\frac{s}{l}$ is everywhere the same and diffuser and blow slot are properly designed.

(3) Power at the blower shaft. The connection between feeding capacity, total pressure jump of the blower, and power at the blower shaft for the flap angle $\eta_{Kl} = 48^\circ$ is represented in figure 18. The power increases in good approximation with the third power of the feeding capacity. For the maximum feeding capacity of $Q = 3.35\ m^3/s$ there results as power requirement at the blower shaft $N_{GW} = 31$ PS (German HP) and a total pressure jump $\Delta p_{ges} = 520\ kg/m^2$. Under the assumption that no losses at all occur at the entrance and in the flow through the wing and that the required pressure head is merely the kinetic energy of the jet leaving the wing, there would

result as minimum power requirement at the blower shaft:

$$N_{min} = \frac{Q\ q_{Str}}{75\ \eta_{blower_{max}}}$$

(with q_{Str} = stagnation pressure of the jet leaving the wing). The ratio

$$\eta_o = \frac{N_{minimum}}{N_{actual}}$$

represents a factor of merit of the arrangement which becomes the larger the smaller the internal pressure losses and the larger the ratio actual/greatest possible blower efficiency.

For this factor of merit one obtains with $f_{blow\ slot} = 0.0474\ m^2$, $\eta_{blower_{max}} = 0.8$ the following values from the measurements:

Q (m^3/s)	N_{Gw} (PS)	$N_{minimum}$ (PS)	$\eta_o = \frac{N_{minimum}}{N_{actual}}$
1.02	0.76	0.49	0.65
1.53	2.40	1.56	.65
2.03	5.93	3.88	.65
2.46	11.31	6.87	.61
2.88	17.87	11.10	.62
3.35	31.18	17.42	.56

One can see that on the average 60 percent of the power actually required would have to be expended also for the ideal case without internal losses.

(4) Total pressure losses. From the mean values of the total pressures immediately ahead of the blower there results the dependence of the mean total pressure loss on the feeding capacity which is represented in figure 18. For a feeding capacity $Q = 2.46\ m^3/s$ the mean total pressures in the throttling vane plane, in the exit cross section of the diffuser, and in the interior of the wing with blowing were also measured. In the following table the separate partial losses are compiled. Since according to the calculation,

performed under C-I $\Delta p_{ges} = q(c_{p_{st}} + n\, c_{Q_s}{}^2)$ and in this case $c_{p_{st}} = 0$, for the test the following will be true:

$$\Delta p_{ges} = q\, n\, c_{Q_s}{}^2 = \frac{\rho}{2}\left(\frac{Q}{F}\right)^2 n$$

The partial losses are therefore represented in the dimensionless form

$$\Delta p_{ges} = n\,\frac{\rho}{2}\left(\frac{Q}{F}\right)^2$$

with the value n according to definition in agreement with the value calculated sub section C-I.

No.	Partial loss	Test values $f\ \Delta p (kg/m^2)$ for $Q = 2.46$ (m^3/s)	$n = \dfrac{\Delta p}{\frac{\rho}{2}\left(\frac{Q}{F}\right)^2} = \dfrac{\Delta p}{q\, c_{Q_s}{}^2}$	Partial loss as percentage of the total
1	Mean loss up to the throttling vane plane	25	0.345×10^4	8.9
2	Loss in the wing with suction, from the throttling vane plane to the blower	20	.277	7.2
3	Blower exit loss. Blower to diffuser exit	40	.555	14.3
4	Mean loss in the wing with blowing	10	.140	3.6
5	Kinetic energy of the jet leaving the wing (= mean stagnation pressure)	170	2.355	60.7
6	Residual	15	.208	5.3
	Total loss	280	3.88	100.0

The residual given in 6 comprises those partial losses which cannot be determined with certainty and also an additional amount of kinetic energy of the jet leaving the wing which is caused by the uneven c_Q-distribution on the wing with blowing. The compilation shows clearly that mainly exit loss and diffuser loss make up the total loss as already mentioned in section C-I.

In order to obtain generally valid dimensionless drag coefficients for the calculation performed in section C-I, the separate partial losses were given in the form $\Delta p = \zeta \frac{\rho}{2} w_{local}^2$. In the following table the partial losses measured for $Q = 2.46\ m^3/s$ are plotted and according to them the equations used for computation and drag coefficient selected in such a manner that the results of calculation and measurement agree (designations as in table 1).

No.	Loss	Formulation of the equation used for computation	Drag coefficient	Calculation Δp	Measurement (kg/m^2)
1	Entrance up to throttling vane plane	$\Delta p_E = \zeta_E \frac{\rho}{2} W_E^2$	$\zeta_E = 1.2$	26	25
2	Loss in the throttling vane plane	$\Delta p_{Dr} = \zeta_{Dr} \frac{\rho}{2} W_{Dr}^2$	$\zeta_{Dr} = 1.0$	6	
3	Friction in the wing with suction	$\Delta p_{RS} = \lambda \frac{\rho}{2} W_S^2 \frac{y_s}{D_{eff}}$ $\lambda = \frac{1}{10^2}\left(\frac{K}{D_{eff}}\right)^{0.314}$; $D_{eff} = \sqrt{\frac{4}{\pi} f_S}$	k = 5m = roughness measure acc. to Hutte I	4	20
4	Turn of ducting-loss in the wing with suction	$\Delta p_{Kr_S} = \zeta_{Kr_S} \frac{\rho}{2} W_S^2$	$\zeta_{Kr_S} = 0.5$	12	
5	Diffuser loss at junction blower - wing with blowing	$\Delta p_D = \zeta_D \frac{\rho}{2} \left(W_{max} - W_{o_B}\right)^2$	$\zeta_D = 1.1$	40	40

No.	Loss	Formulation of the equation used for computation	Drag coefficient	Calculation Δp	Measurement (kg/m^2)
6	Turn of ducting-loss in the wing with blowing	$\Delta p_{Kr_B} = \zeta_{Kr_B} \frac{\varrho}{2} w_{o_B}^2$	$\zeta_{Kr_B} = 0.4$	12	25 (with residual)
7	Friction in the wing with blowing	$\Delta p_{RB} = \lambda \frac{\varrho}{2} w_{o_B}^2 \frac{y_B}{D_{eff}}$ $\lambda = \frac{1}{10^2}\left(\frac{K}{D_{eff}}\right)^{0.314}$; $D_{eff} = \sqrt{\frac{4}{\pi} f_{Bmi}}$	$k = 5$ m	10	
8	Kinetic energy in the jet for blowing	$\Delta p_A = \frac{\varrho}{2} w_A^2$		170	170
		Sum:		280	280

The drag coefficients of this table agree satisfactorily with the values measured on single turns of ducting and diffusers and were taken as basis for the general calculation of the section C-I.

D-II. MEASUREMENT RESULTS ON PRESSURE LOSSES AND POWER REQUIREMENT

ARRANGEMENT II. BLOWING OVER THE ENTIRE SPAN

These measurements were carried out by W. Schwier - AVA - by order of the firm Messerschmitt A. G., Augsburg, and were not published so far. Here only the main results which are of interest in this connection will be given.

A. Model Description and Test Procedure

The test wing is a half wing of 4.20 meters semispan which is furnished with a continuous HP flap. For the feeding of air a two-stage axial blower of 300 millimeters outer diameter and hub ratio 0.5 is installed. The essential arrangement of the blower can be seen from figure 9. The ratio blow slot width/wing chord remains constant along the span and is $\frac{s}{l} = 0.008$. The main length and area ratios are the following:

$$y/l_{mi} = 2.68 \qquad K_1 = \frac{f_H}{f_G} = 1.25$$

$$l_{mi}/l_G = 0.94$$

$$D/l_G = 0.18$$ Rear spar located at 50 percent chord

$$\upsilon = 0.5$$

$$\frac{s}{l} = 0.008$$

The feeding capacity was calculated from the static-pressure decrease in the blower entrance cross section. By means of throttling and guiding vanes in the wing a sufficiently uniform c_Q-distribution along the span was obtained. For determination of the distribution of the feeding capacity at the blow slot the velocity profiles of the jet leaving the wing were measured with the aid of a total pressure rake. The pressure rise of the blower could be measured on static-pressure holes ahead of and behind the blower.

B. Test Results

(1) The c_Q-distribution along the span is even without any guiding vanes quite favorable. Additional installation of throttling and guiding vanes improved it still more.

(2) Total pressure loss. The pressure loss increases in good approximation as the second power of the feeding capacity. The values measured for a feeding capacity of $Q = 3\ m^3/S$ were:

Without throttling vanes $\Delta p = 405(kg/m^2)$

With throttling vanes $\Delta p = 470(kg/m^2)$

The exit loss alone amounts to 220 kg/m^2.

In the calculation performed under C-II thin total pressure loss is subdivided into the four partial losses:

Δp_E	entrance loss
Δp_D	diffuser loss behind blower
Δp_{exp}	loss by sudden expansion behind the rear spar
Δp_A	exit loss

For these partial losses the equation used for computation contained in table 2 is made. Since the partial losses were not measured separately, the loss coefficient $\zeta = \frac{\Delta p}{\frac{\rho}{2} {w_{local}}^2}$ had to be estimated. For $Q = 3\ m^3/s$ calculation and measurement agree well with respect to the magnitude of the pressure loss if one selects the following values for ζ:

$\zeta_E = 0.1$

$\zeta_D = 0.5$

$\zeta_{exp} = 1.0$ for the case without guiding and throttling vanes

$= 1.5$ for the case with guiding and throttling vanes

These values are altogether probable.

For the measured feeding capacity $Q = 3.0 \ m^3/s$ one obtains with the estimated loss coefficients the following portioning of the total loss:

No.	Loss	Formulation	Flow cross section (m^2)	$\Delta p (kg/m^2)$ for $Q = 3$ (m^3/s)		Percentage of the partial loss contributed to the total loss	
				Without guiding vane	With guiding vane	Without guiding vane	With guiding vane
1	Δp_E	$\zeta_E \frac{\rho}{2} W_E^2$	$f_E = 0.071$	11.0	11.0	3.0	2.5
2	Δp_D	$\zeta_D \left(\frac{\rho}{2} W_G^2 - \frac{\rho}{2} W_H^2\right)$	$f_G = 0.053$ $f_H = 0.066$	35.5	35.5	9.0	7.5
3	Δp_{Exp}	$\zeta \frac{\rho}{2} W_H^2$	$f_H = 0.066$	129.0	194.0	32.5	42.0
4	Δp_A	$\frac{\rho}{2} W_A^2$	$f_D = 0.0505$	220.0	220.0	55.5	48.0
Δp Calculation				395.5	460.5	100.0	100.0
Δp Measured				405.0	470.0		

E. COMPARISON OF THE THREE ARRANGEMENTS WITH THE AID OF AN EXAMPLE

Following the pressure-loss coefficient and the feed-power requirement are calculated for a certain airplane to obtain a clear picture of the proportions of the investigated three arrangements to each other.

For all three arrangements the following common assumptions are made:

(1) Trapezoidal wing, taper 1:2 aspect ratio 7.5

(2) Thickness ratio at the root 18 percent, at the tip 10 percent

(3) For flows in the direction of the spar only the space behind the rear spar is at disposal

(4) Slot width ratio $\left(\frac{s}{l}\right)_s = 0.03$, $\left(\frac{s}{l}\right)_B = 0.0075$

(5) Flow ducts are provided with flat sheet covering

(6) Feeding of the air takes place through an axial blower of the hub ratio $(d/D) = \nu = 0.5$, efficiency 70 percent

For arrangement I it is assumed:

$$F/F_{ae} = 0.45; \quad c_{p_{st}} = 2.0$$

Arrangement II: $F/F_{ae} = 0.9; \quad c_{p_{st}} = -1.0$

Arrangement III: $F/F_{ae} = 0.9; \quad c_{p_{st}} = 2.0$

The length and area ratios, respectively, decisive for the magnitude of the pressure loss are:

For arrangement I: D/l_G

For arrangement II: $D/l_G \; (l_{mi}/l_G = 0.94)$

For arrangement III: $f_{G_a}/f_R^{\otimes}$, $f_A/f_R^{\otimes}$

The interesting values (pressure-loss coefficient and feed power) are calculated for all three arrangements as functions of the values above which can be changed arbitrarily; for arrangements I and II from the rule-of-thumb formulas of sections C-I and II, for arrangement III from the results of the calculation not published here.

Arrangement I

D/l_G	$1/10^4\ n$
0.08	12.18
.10	5.44
.12	3.38
.14	2.71
.16	2.50
.18	2.50

Arrangement II

D/l_g	$1/10^4\ n$
0.08	71.0
.10	30.2
.12	15.5
.14	9.2
.16	6.1
.18	4.5
.20	3.6

Arrangement III

$F_{G_a}/f_R{}^{\odot}$	$1/10^4\ n$			
	$\frac{F_A}{F_R{}^{\odot}} = 0.2$	$\frac{F_A}{F_R{}^{\odot}} = 0.4$	$\frac{F_A}{F_R{}^{\odot}} = 0.6$	$\frac{F_A}{F_R{}^{\odot}} = 0.8$
0.1	7.2	6.6	6.4	6.4
.2	3.0	2.3	2.2	2.2
.3	2.1	1.6	1.5	1.5
.4	1.9	1.3	1.2	1.2
.5	2.0	1.5	1.4	1.4
.6	2.2	1.7	1.6	1.6

According to equation (B-3) (section B) the power required is proportional to the feed-power coefficient c_l and the area ratio F/F_{ae}, thus:

$$N \sim \frac{F}{F_{ae}} c_l \sim \frac{F}{F_{ae}} \frac{c_{p_{st}}\ c_Q + n\ c_Q{}^3}{c_a{}^{3/2}} \sim c_{l_{eff}}$$

It is assumed for this comparative calculation that for obtaining a $c_a = 3.5$ for suction and blowing a $c_{Q_{local}} = 0.015$ is necessary which about corresponds to the actual conditions according to the present state of high lift research.

Then one obtains the following numerical values for the expression $c_{l_{eff}} = \frac{F}{F_{ae}} c_l$ which is directly proportional to the feed power required

$$N = \frac{1}{75\eta}\sqrt{\frac{G^3 l}{F_{ae}\,\rho}}\left(\frac{F}{F_{ae}} c_l\right)$$

I

$\frac{D}{l_G}$	$c_{l_{eff}} = \frac{F}{F_{ae}} c_l$
0.08	0.0304
.10	.0147
.12	.0099
.14	.0084
.16	.0079
.18	.0079

II

$\frac{D}{l_G}$	$c_{l_{eff}} = \frac{F}{F_{ae}} c_l$
0.08	0.327
.10	.138
.12	.070
.14	.041
.16	.026
.18	.019
.20	.015

III

$c_{l_{eff}} = \frac{F}{F_{ae}} c_l$		f_A/f_R®			
		0.2	0.4	0.6	0.8
$\frac{f_{Ga}}{f_R}$®	0.1	0.0375	0.0347	0.0338	0.0338
	.2	.0180	.0148	.0143	.0143
	.3	.0139	.0116	.0111	.0111
	.4	.0129	.0102	.0097	.0097
	.5	.0134	.0111	.0106	.0106
	.6	.0143	.0121	.0116	.0116

In figures 19 and 20 $c_{l_{eff}} = \frac{F}{F_{ae}} c_l$ for the three arrangements is plotted as function of the decisive length and area ratios. One can see from this example that the feed-power requirement for all three types of construction can be made about equal if one only provides sufficiently large flow cross sections. For equal feed-power requirement the construction type I (compound action) is clearly superior to the two other types since the space behind the rear spar is usually available and since no essential disturbances of the inner construction or of the outer shape of the airplane are caused by the installation of the boundary-layer apparatus.

Figure 21 shows the feed-power requirement per unit weight (PS German HP/kg) as function of the wing loading and the structural conditions for $c_a = 3.5$ and $c_Q = 0.015$. The curves are valid under the assumptions made at the beginning of section E. The specific feed power can be calculated from:

$$\frac{N}{G} = \frac{1}{75\eta} \sqrt{\frac{G}{F_{ae}} \frac{2}{\rho}}\, c_{l_{eff}}$$

F. SUMMARY AND DEDUCTIONS

The results of calculations and measurements with respect to the power requirement of airplanes with boundary-layer control are given. It is shown that of the investigated, structurally possible arrangements:

I. Suction in the landing-flap region, blowing in the aileron region

II. Blowing over the entire span

III. Suction over the entire span

arrangement I is superior to the other types of construction. In general, one may for all types of construction assume that the feeding-capacity coefficient c_Q required for a certain c_a plays the main part for the power requirement and the pressure loss, respectively, whereas the pressure coefficient $c_{p_{st}}$ which covers only the difference of the static pressures at the suction and blowing point is of lesser importance. For all three cases it is very important for obtaining small feed powers to make the narrowest cross section of the feed apparatus (blower or jet apparatus) as large as possible since the kinetic energy of the flow at this location is lost to a great part. The construction type I offers the great advantage that the entire arrangement (feed apparatus and air ducts) is installed behind the rear spar of the wing structure whereas for the type II spar perforations are necessary and for type III a part of the loading space in the fuselage is lost to flow ducts.

Translation by Mary L. Mahler
National Advisory Committee
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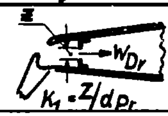
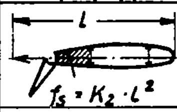
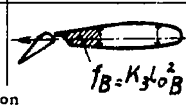
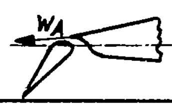
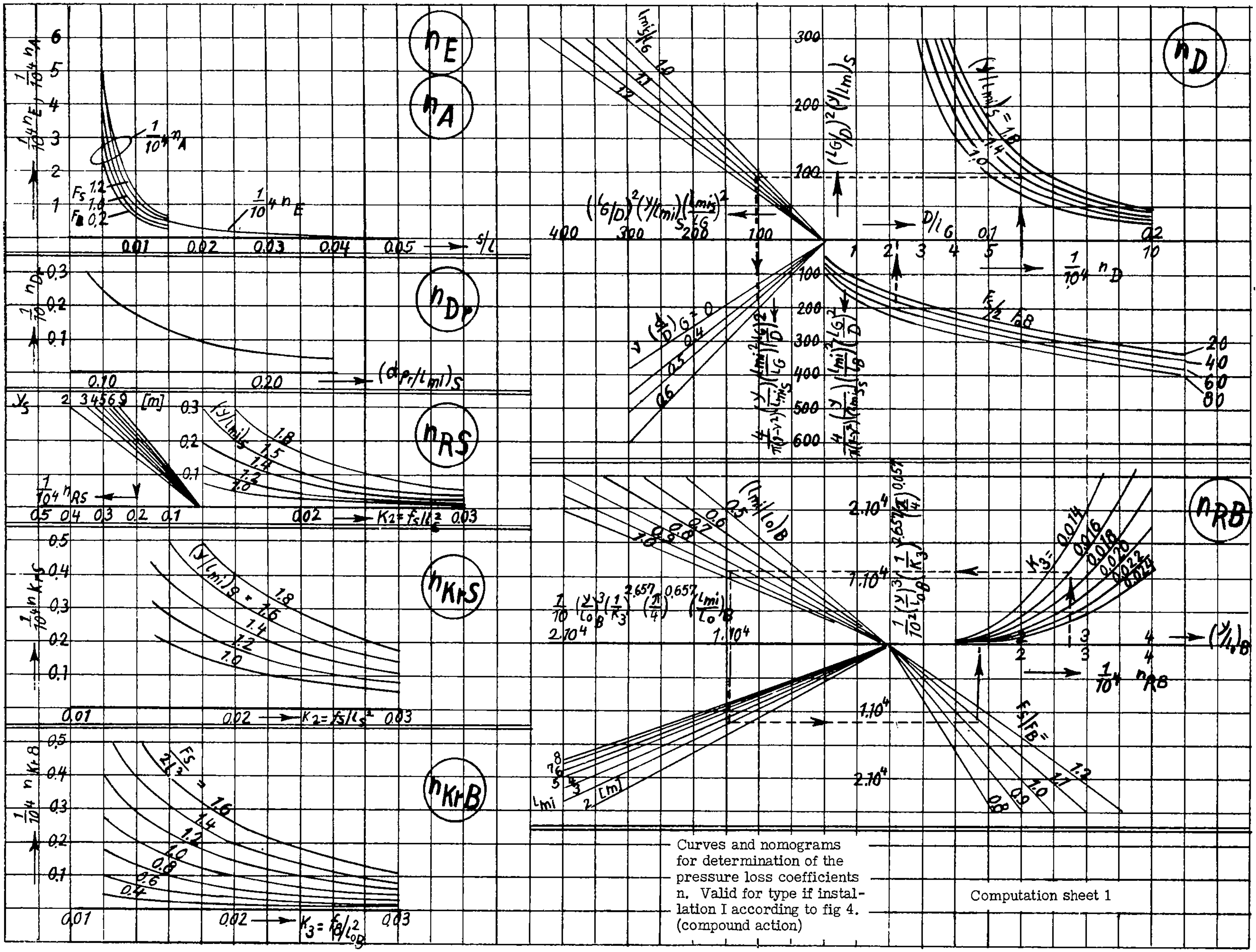
Loss	Formulation for the calculation	Sketch	General form	Test values	Pressure loss coefficient n
Δp_E Entrance	$\zeta_E \frac{\varrho}{2} w_E^2$		$q c_{Q_S}^2 \zeta_E \left(\frac{l}{s}\right)_S^2$	$\zeta_E = 1{,}2$	$n_E = \zeta_E \left(\frac{l}{s}\right)_S^2$
Δp_{Dr} Throttling	$\zeta_{Dr} \frac{\varrho}{2} w_{Dr}^2$	 $K_1 = Z/d_{Pr}$	$q c_{Q_S}^2 \zeta_{Dr} \left(\frac{1}{K_1 (d_{Pr}/l_{mi})_S}\right)^2$	$\zeta_{Dr} = 1{,}0$ $K_1 \approx 0{,}2$	$n_{Dr} = \zeta_{Dr} \left(\frac{1}{K_1 (d_{Pr}/l_{mi})_S}\right)^2$
Δp_{RS} Friction suction wing	$\lambda \frac{\varrho}{2} w_S^2 \frac{y_S}{D_{eff}}$ $D_{eff} = \sqrt{\frac{4}{\pi} f_S}$ $\lambda = \frac{1}{10^2}\left(\frac{K}{D_{eff}}\right)^{0{,}314}$	 $f_S = K_2 \cdot l^2$	$q c_{Q_S}^2 \frac{1}{10^2}\left(\frac{K}{l_{mi_S}}\right)^{0{,}314}\left(\frac{y}{l_{mi}}\right)_S^3\left(\frac{1}{K_2}\right)^{2{,}657}\left(\frac{\pi}{4}\right)^{0{,}657}$	$K = 5{,}0\,m$ Roughness measure according to Hutte I	$n_{RS} = \frac{1}{10^2}\left(\frac{K}{l_{mi_S}}\right)^{0{,}314}\left(\frac{y}{l_{mi}}\right)_S^3\left(\frac{1}{K_2}\right)^{2{,}657}\left(\frac{\pi}{4}\right)^{0{,}657}$
Δp_{KrS} Turn suction wing	$\zeta_{KrS} \frac{\varrho}{2} w_S^2$		$q c_{Q_S}^2 \zeta_{KrS} \left(\frac{y}{l_{mi}}\right)_S^2 \left(\frac{1}{K_2}\right)^2$	$\zeta_{KrS} = 0{,}5$	$n_{KrS} = \zeta_{KrS} \left(\frac{y}{l_{mi}}\right)_S^2 \left(\frac{1}{K_2}\right)^2$
Δp_D Diffuser	$\zeta_D \frac{\varrho}{2} (w_G - w_{oB})^2$ w_G = Velocity in the annular cross section	 $f_B = K_3 l_{oB}^2$	$q c_{Q_S}^2 \zeta_D \left[\frac{4}{\pi(1-\nu^2)}\left(\frac{y}{l_{mi}}\right)_S\left(\frac{l_{mi_S}}{l_G}\right)^2\left(\frac{l_G}{D}\right)^2 - \frac{F_S}{2K_3 l_{oB}^2}\right]^2$	$\zeta_D = 1{,}1$	$n_D = \zeta_D \left[\frac{4}{\pi(1-\nu^2)}\left(\frac{y}{l_{mi}}\right)_S\left(\frac{l_{mi_S}}{l_G}\right)^2\left(\frac{l_G}{D}\right)^2 - \frac{F_S}{2K_3 l_{oB}^2}\right]^2$
Δp_{KrB} Turn blow wing	$\zeta_{KrB} \frac{\varrho}{2} w_{oB}^2$		$q c_{Q_S}^2 \zeta_{KrB} \left(\frac{F_S}{2K_3 l_{oB}^2}\right)^2$	$\zeta_{KrB} = 0{,}4$	$n_{KrB} = \zeta_{KrB} \left(\frac{F_S}{2K_3 l_{oB}^2}\right)^2$
Δp_{RB} Friction blow wing	$\lambda \frac{\varrho}{2} w_{oB}^2 \frac{y_B}{D_{eff}}$ $D_{eff} = \sqrt{\frac{4}{\pi} f_{B_{mi}}}$ $\lambda = \frac{1}{10^2}\left(\frac{K}{D_{eff}}\right)^{0{,}314}$		$q c_{Q_S}^2 \left[\left(\frac{F_S}{F_B}\right)^2 \frac{1}{10^2}\left(\frac{K}{l_{mi_B}}\right)^{0{,}314}\left(\frac{y}{l_o}\right)_B^3\left(\frac{l_{mi}}{l_o}\right)_B\left(\frac{1}{K_3}\right)^{2{,}657}\left(\frac{\pi}{4}\right)^{0{,}657}\right]$	$K = 5{,}0\,m$	$n_{RB} = \left(\frac{F_S}{F_B}\right)^2 \frac{1}{10^2}\left(\frac{K}{l_{mi_B}}\right)^{0{,}314}\left(\frac{y}{l_o}\right)_B^3\left(\frac{l_{mi}}{l_o}\right)_B\left(\frac{1}{K_3}\right)^{2{,}657}\left(\frac{\pi}{4}\right)^{0{,}657}$
Δp_A Exit	$\frac{\varrho}{2} w_A^2$		$q c_{Q_S}^2 \left(\frac{F_S}{F_B}\right)^2 \left(\frac{l}{s}\right)_B^2$		$n_A = \left(\frac{F_S}{F_B}\right)^2 \left(\frac{l}{s}\right)_B^2$

TABLE 1

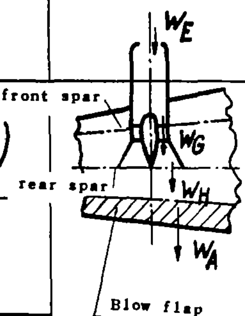
FOR CALCULATION OF THE PRESSURE LOSS COEFFICIENT $n = \frac{\Delta p}{q c_{Q_s}^2}$ FOR THE CASE

OF INSTALLATION OF ARRANGEMENT I [Compound arrangement according to figure 4]



Curves and nomograms for determination of the pressure loss coefficients n. Valid for type if installation I according to fig 4. (compound action)

Computation sheet 1

Loss	Formulation for the calculation	Sketch	General form	Test values	Pressure loss coefficient n
Δp_E Entrance	$\zeta_E \frac{\varrho}{2} w_E^2$		$q c_Q^2 \zeta_E \left[\frac{4}{\pi}\left(\frac{y}{l_{mi}}\right)\left(\frac{l_{mi}}{l_G}\right)^2\left(\frac{l_G}{D}\right)^2\right]^2$	$\zeta_E = 0{,}1$	$n_E = \zeta_E\left[\frac{4}{\pi}\left(\frac{y}{l_{mi}}\right)\left(\frac{l_{mi}}{l_G}\right)^2\left(\frac{l_G}{D}\right)^2\right]^2$
Δp_D Diffuser	$\zeta_D\left(\frac{\varrho}{2}w_G^2 - \frac{\varrho}{2}w_H^2\right)$		$q c_Q^2 \zeta_D\left[\frac{4}{\pi(1-\nu^2)}\right]^2\left[1-\left(\frac{1}{K_1}\right)^2\right]\left[\frac{y}{l_{mi}}\left(\frac{l_{mi}}{l_G}\right)^2\left(\frac{l_G}{D}\right)^2\right]^2$	$\zeta_D = 0{,}5$	$n_D = \zeta_D\left[\frac{4}{\pi(1-\nu^2)}\right]^2\left[1-\left(\frac{1}{K_1}\right)^2\right]\left[\frac{y}{l_{mi}}\left(\frac{l_{mi}}{l_G}\right)^2\left(\frac{l_G}{D}\right)^2\right]^2$
Δp_{Exp} Sudden expansion	$\zeta \frac{\varrho}{2} w_H^2$		$q c_Q^2 \zeta\left[\frac{4}{\pi(1-\nu^2)}\right]^2\left(\frac{1}{K_1}\right)^2\left[\frac{y}{l_{mi}}\left(\frac{l_{mi}}{l_G}\right)^2\left(\frac{l_G}{D}\right)^2\right]^2$	$\zeta = 1{,}2$	$n_{Exp} = \zeta\left[\frac{4}{\pi(1-\nu^2)}\right]^2\left(\frac{1}{K_1}\right)^2\left[\frac{y}{l_{mi}}\left(\frac{l_{mi}}{l_G}\right)^2\left(\frac{l_G}{D}\right)^2\right]^2$
Δp_A Exit loss	$\frac{\varrho}{2} w_A^2$	$\frac{f_H}{f_G} = K_1$	$q c_Q^2 \left(\frac{l}{s}\right)^2$		$n_A = \left(\frac{l}{s}\right)^2$

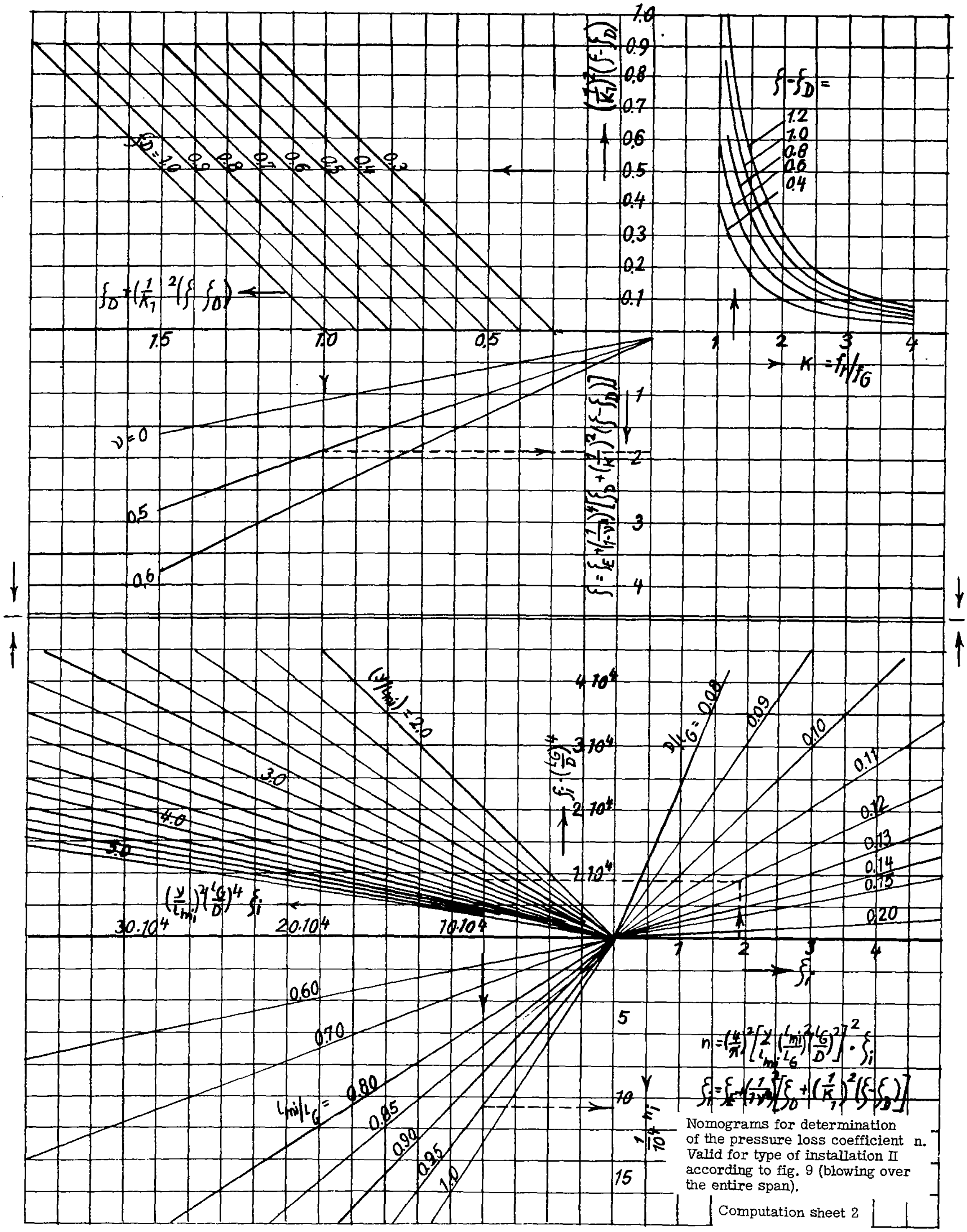
Δp_e, Δp_D, Δp_{Exp} are functions of the same variable(s) and are combined

Loss		Pressure loss coefficient	Test values
$\Delta p_{E+D+Exp}$ Inner losses	$\zeta_E \frac{\varrho}{2} w_E^2 + \zeta_D\left(\frac{\varrho}{2}w_G^2 - \frac{\varrho}{2}w_H^2\right) + \zeta\frac{\varrho}{2}w_H^2$	$n_i = \left(\frac{4}{\pi}\right)^2\left[\frac{y}{l_{mi}}\left(\frac{l_{mi}}{l_G}\right)^2\left(\frac{l_G}{D}\right)^2\right]^2\left[\zeta_E + \left(\frac{1}{1-\nu^2}\right)^2\left\{\zeta_D + \left(\frac{1}{K_1}\right)^2\left(\zeta - \zeta_D\right)\right\}\right]$	$\zeta_E = 1{,}0$ $\zeta_D = 0{,}5$ $\zeta = 1{,}2$
Δp_A Exit loss	$\frac{\varrho}{2} w_A^2$	$n_A = \left(\frac{l}{s}\right)^2$	

TABLE 2

FOR CALCULATION OF THE PRESSURE LOSS COEFFICIENT $n = \frac{\Delta p}{q c_Q^2 s}$ FOR THE CASE

OF INSTALLATION II [Blowing over the entire span according to figure 9]



Nomograms for determination of the pressure loss coefficient n. Valid for type of installation II according to fig. 9 (blowing over the entire span).

Computation sheet 2

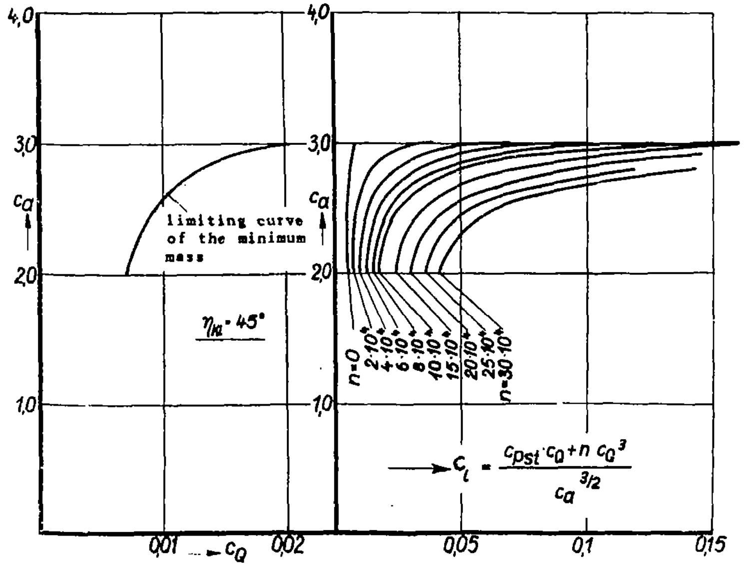


Figure 1.- Profile 23012.

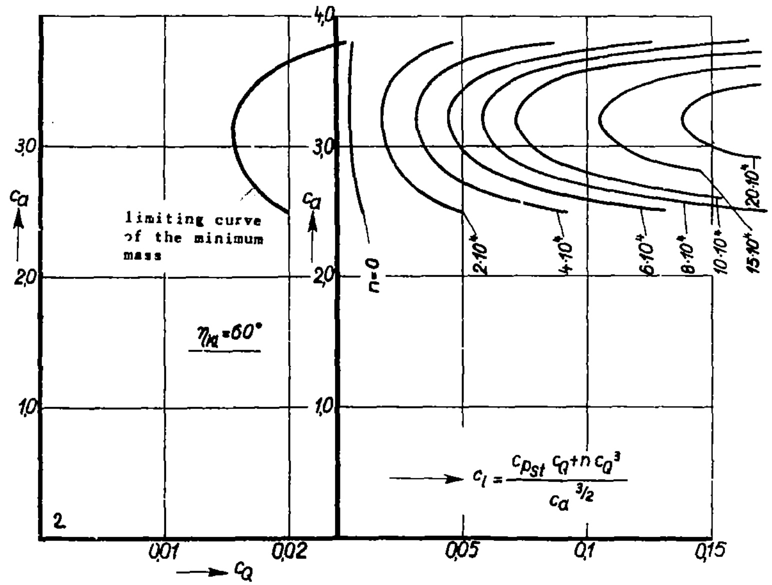


Figure 2.- Profile 23015

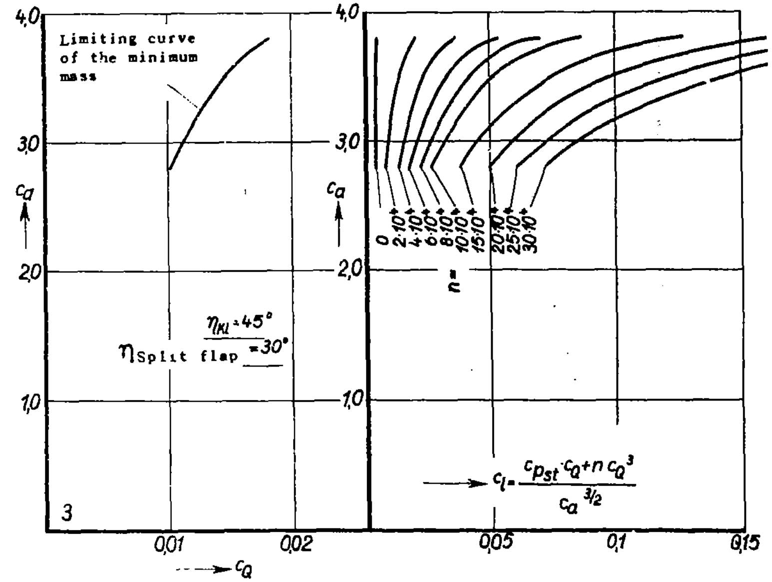


Figure 3.- Profile 23018.

Figure 1 to 3.- Feeding capacity coefficient c_Q and feed power coefficient c_l as functions of c_a and pressure loss coefficient n. Valid for suction flap wings with $\frac{l_{Kl}}{l} = 0.20$.

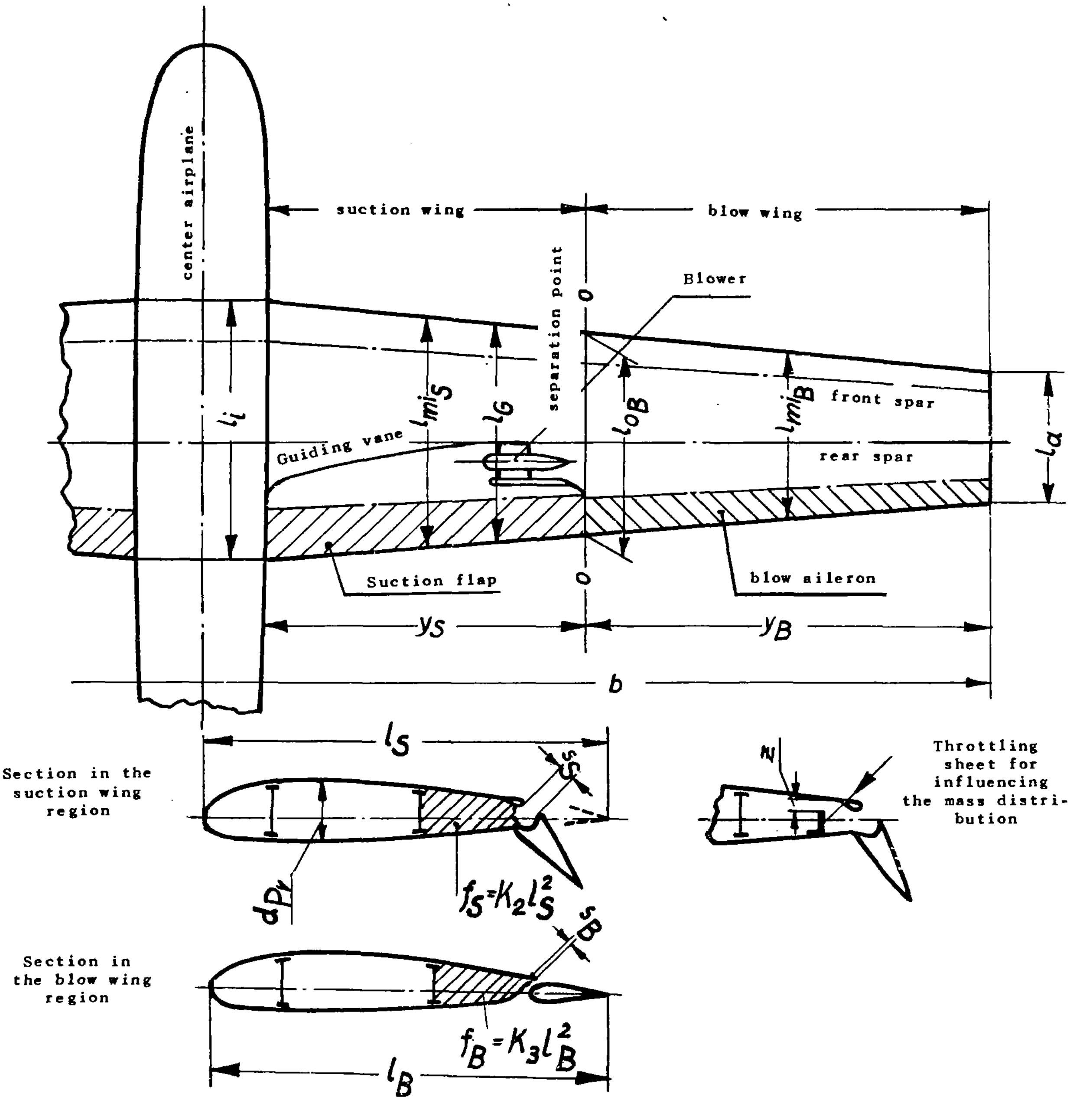
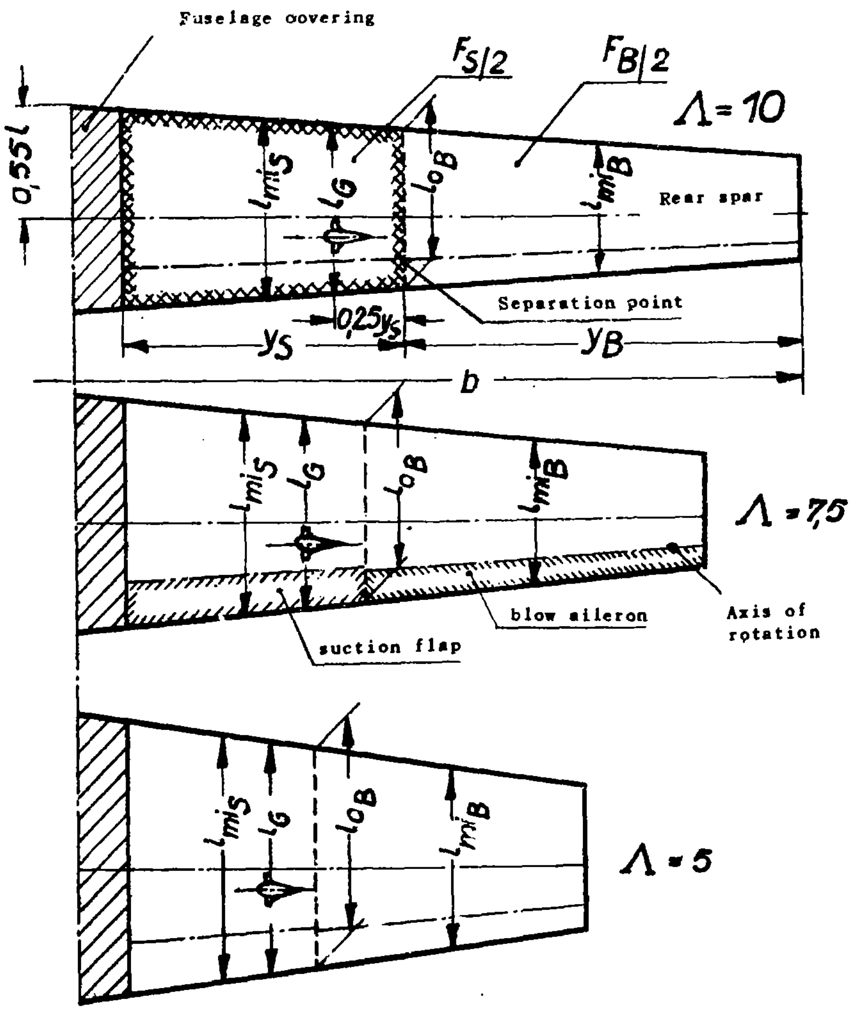


Figure 4.- Arrangement I. Compound arrangement. Suction in the flap region; blowing in the aileron region. Entire feed apparatus behind the rear spar of the wing.



Λ	10,0	7,5	5
F_S/F_B	1,0	1,0	1,0
$(y/l_{mi})_S$	1,65	1,25	0,80
$(l_{mi}/l_G)_S$	1,07	1,06	1,05
$(y/l_o)_B$	2,60	2,00	1,30
$(l_{mi}/l_o)_B$	0,83	0,83	0,83
$(d_{pr}/l_{mi})_S$	0,16	0,16	0,16
$(d_{pr}/l_{mi})_B$	0,12	0,12	0,12
$K_1 = \frac{z}{d_{pr}}$	0,20	0,20	0,20
$K_2 = \frac{f_S}{l_S^2}$	0,025	0,025	0,025
$K_3 = \frac{f_B}{l_B^2}$	0,022	0,022	0,022
$F_S/2\,l_{oB}^2$	2,06	1,6	1,03

Figure 5.- Length and area ratios of the three trapezoidal wings investigated numerically.

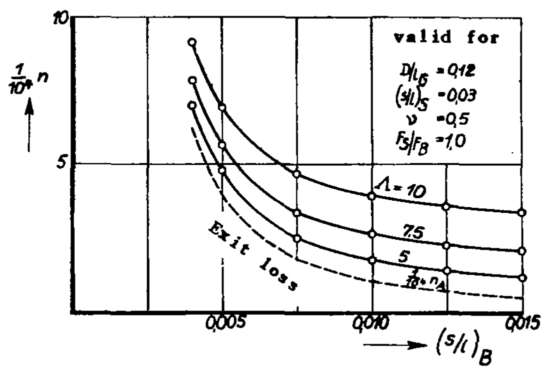


Figure 6.- Pressure loss coefficient $n = \frac{\Delta p_V}{q\, c_Q^{\,2}{}_S}$ as a function of the aspect ratio Λ and slot width ratio $\left(\frac{s}{l}\right)_B$ for arrangement I (compound arrangement according to figure 4). Valid for trapezoidal wings with taper ratio 1:2.

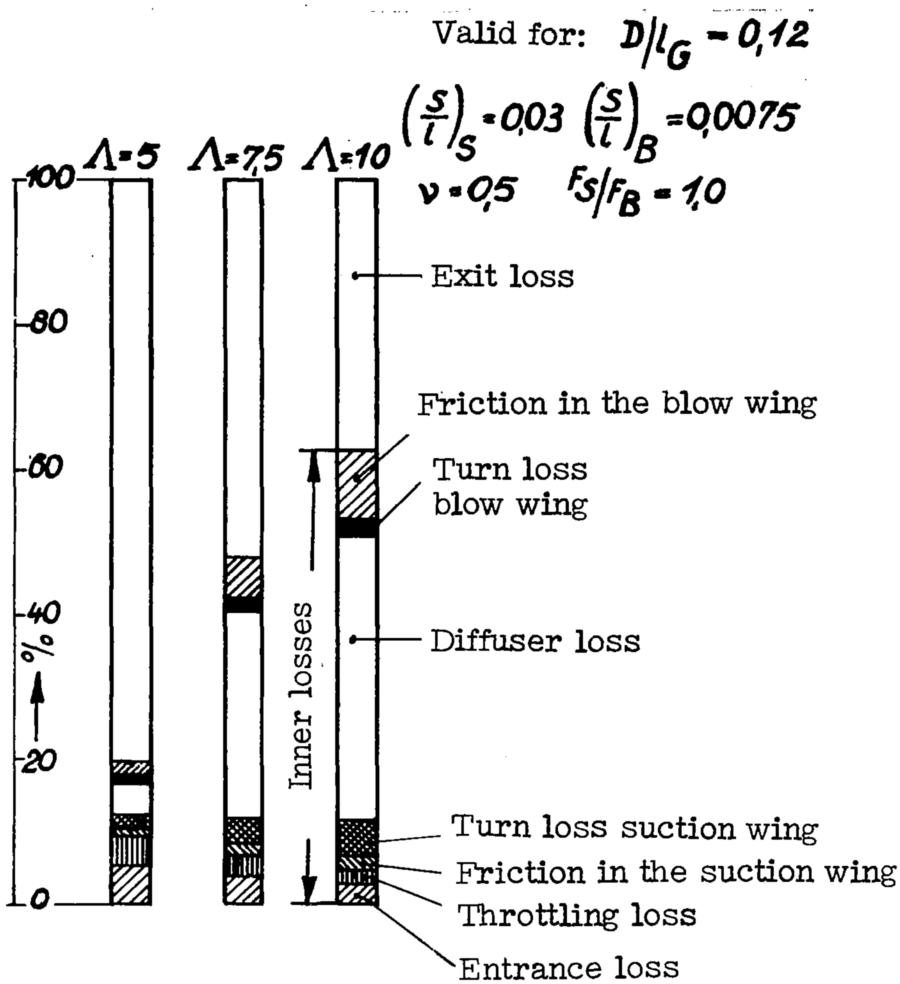
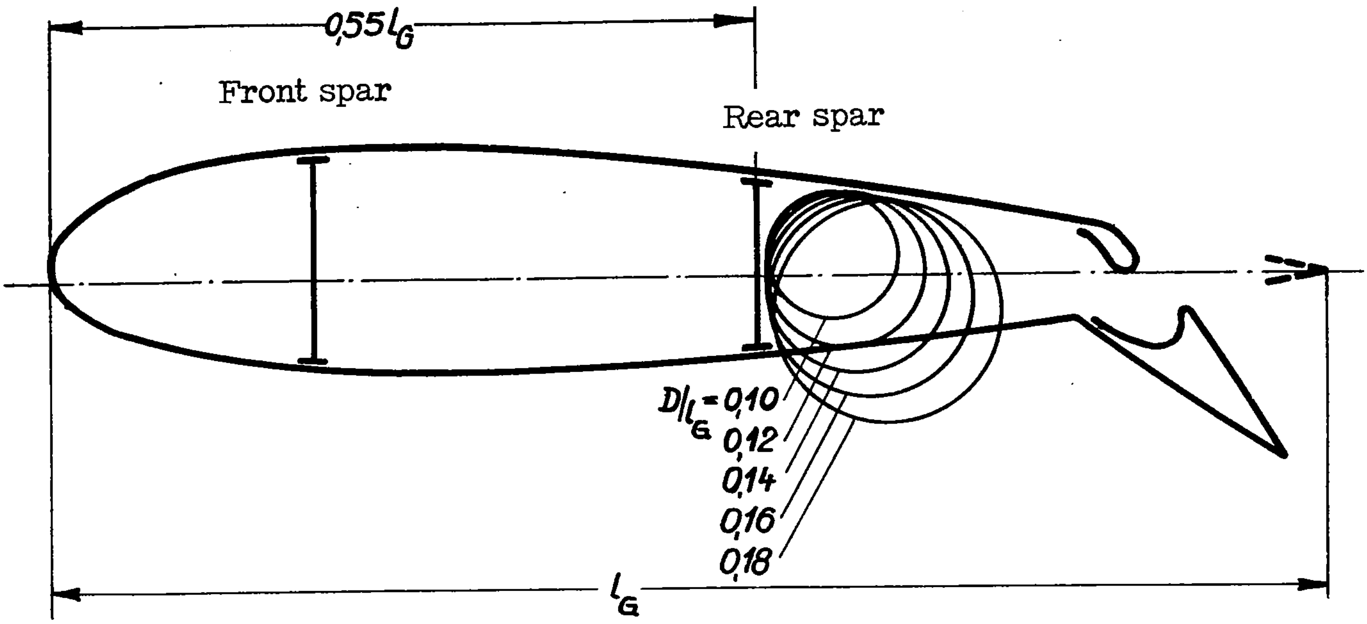


Figure 7.- Contribution of the separate pressure losses to the total loss for various aspect ratios. Arrangement I (compound arrangement according to figure 4), trapezoidal wing (according to figure 5).



Profile 23018

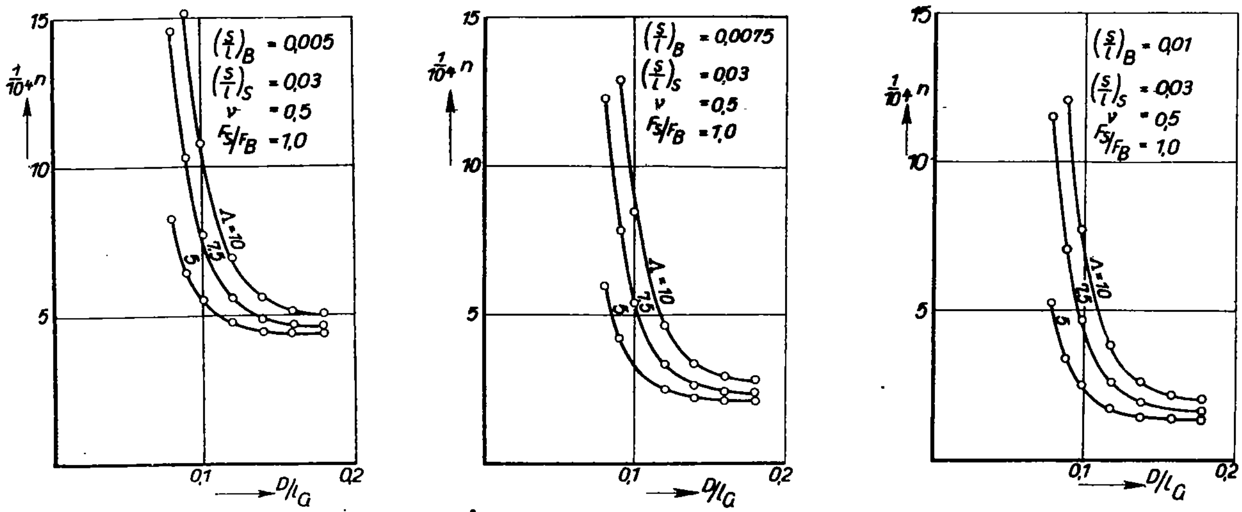


Figure 8.- Pressure loss coefficient $n = \dfrac{\Delta p_V}{q\, c_{Q}{}^2{}_s}$ as a function of the aspect ratio and of the ratio "blower diameter/wing chord at the location of the blower" for three blow slot widths. Arrangement I (compound arrangement according to figures 4 and 5).

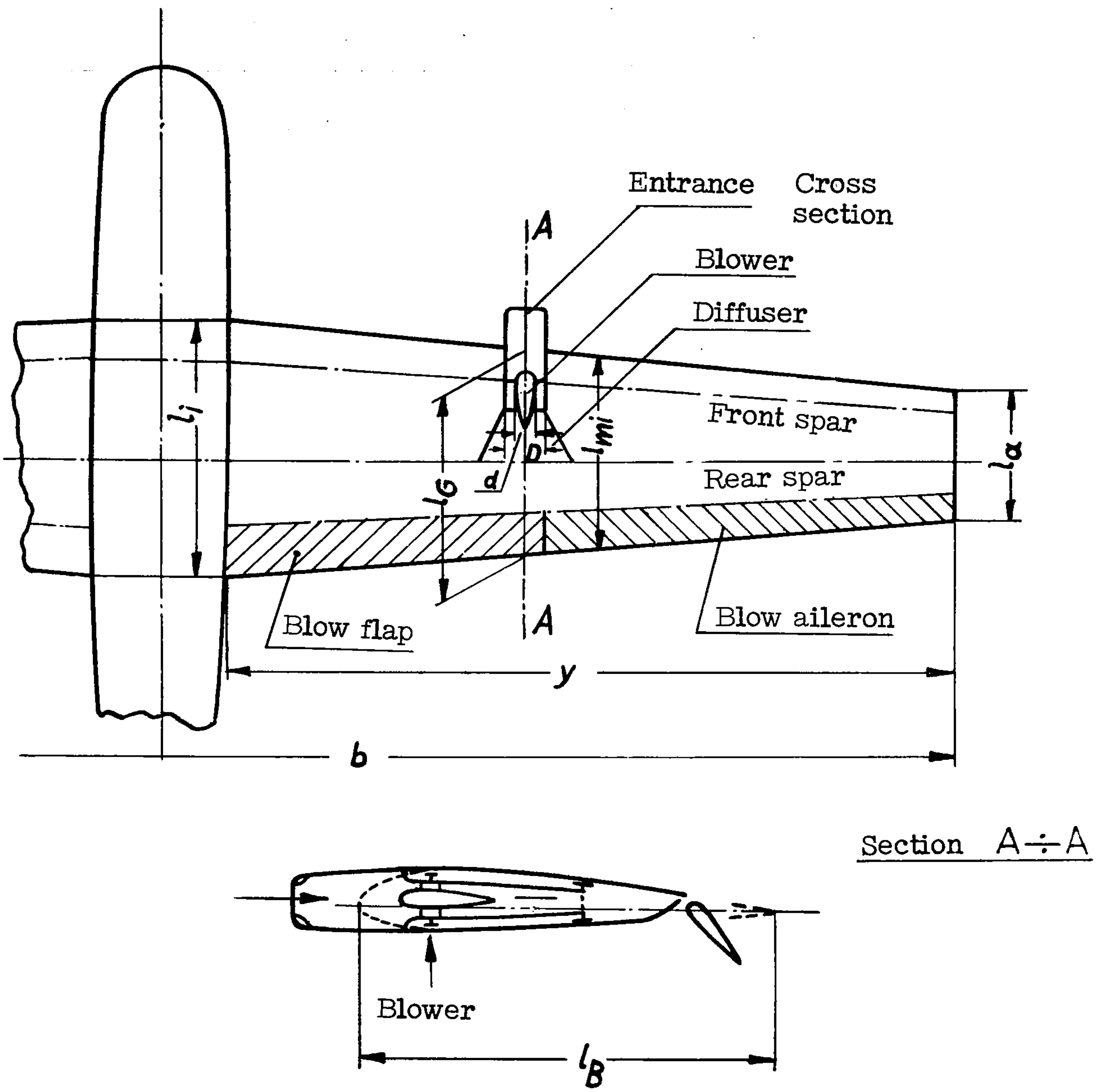


Figure 9.- Arrangement II. Blowing over the whole span. Entire feed apparatus in the wing.

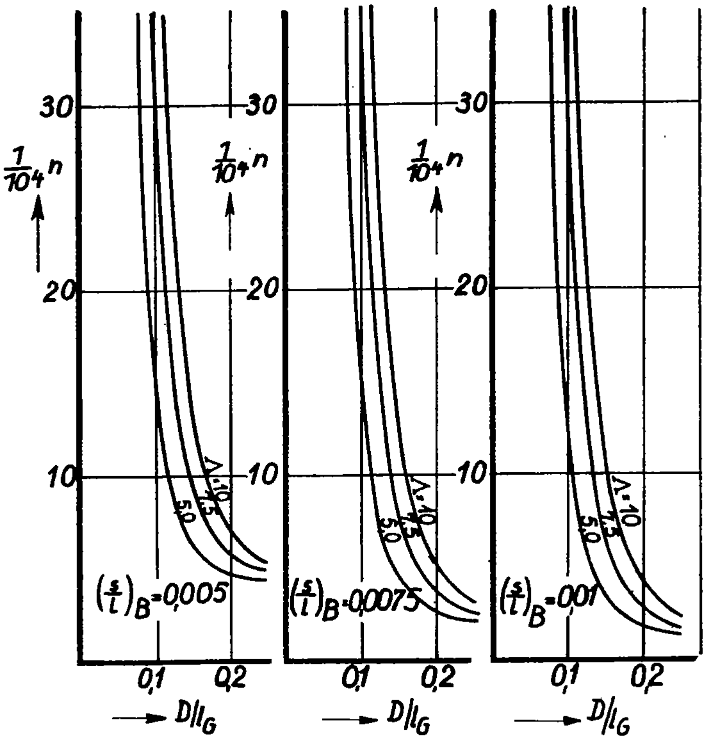


Figure 10.- Influence of the ratio "blower diameter/wing chord at the location of the blower" on the pressure loss coefficient for various aspect ratios and slot width ratios. Valid for installation form II (figure 9) and $\nu = 0.5$, $\frac{l_{mi}}{l_G} = 0.94$.

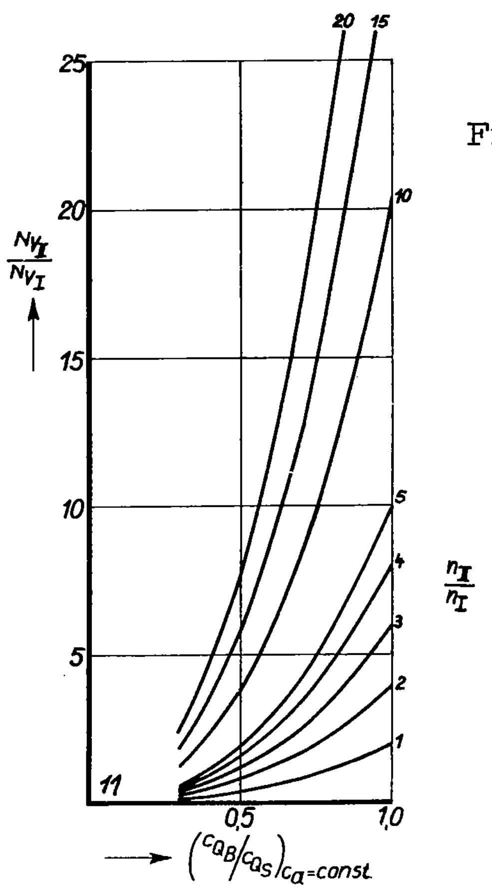


Figure 11.- Ratio of the powers spent due to loss N_V as a function of the ratio feeding capacity requirement/pressure loss coefficients. Case I: Suction and blowing. Case II: Blowing.

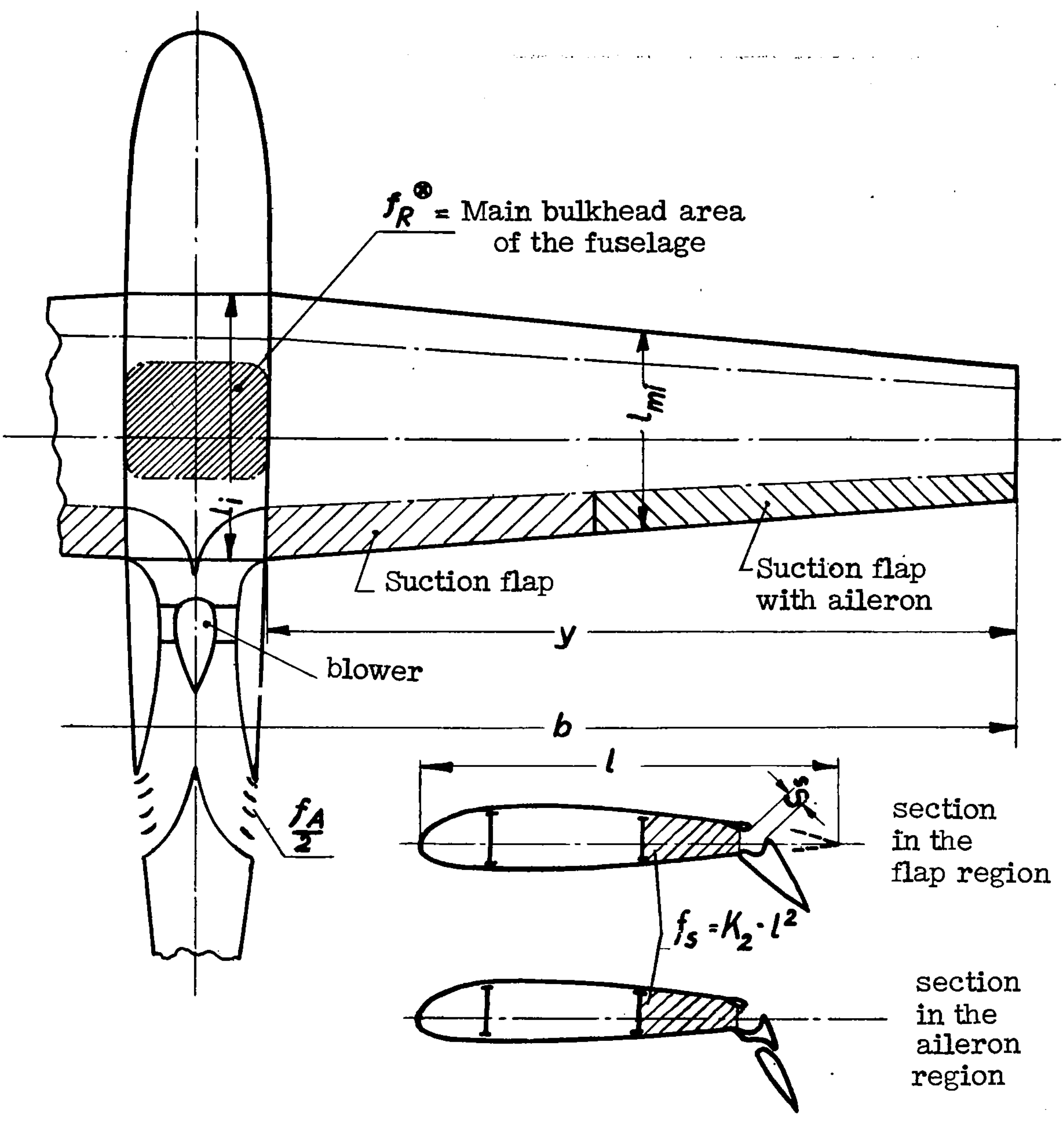


Figure 12.- Arrangement III. Suction over the whole span. Entire feed apparatus in the fuselage.

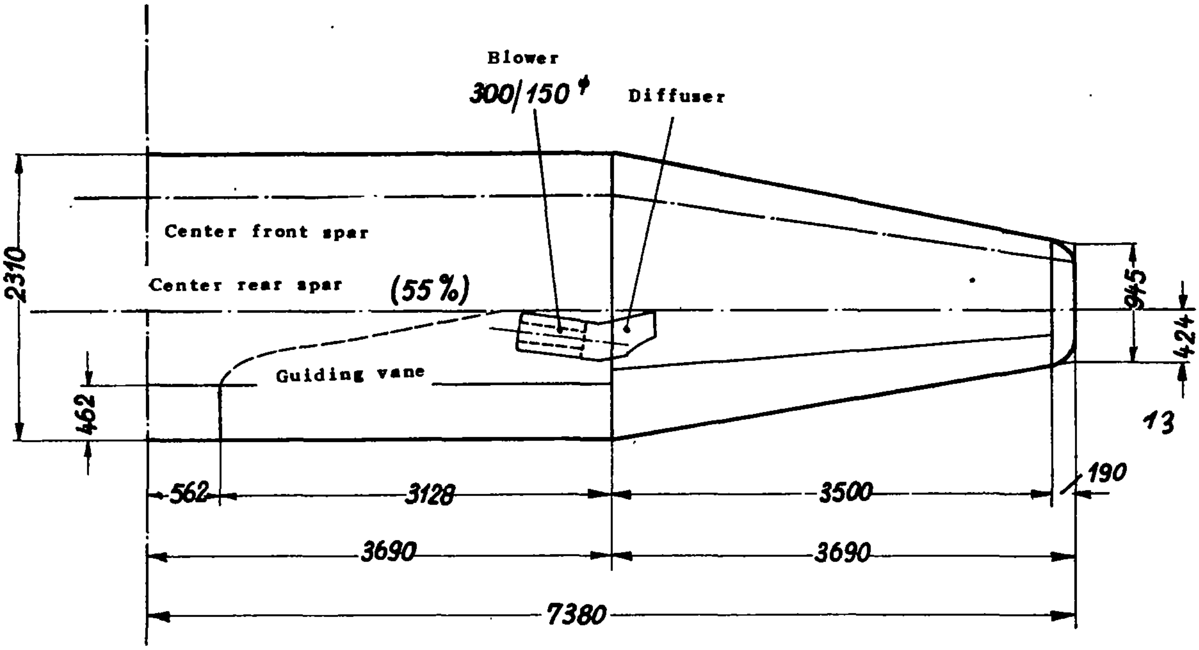
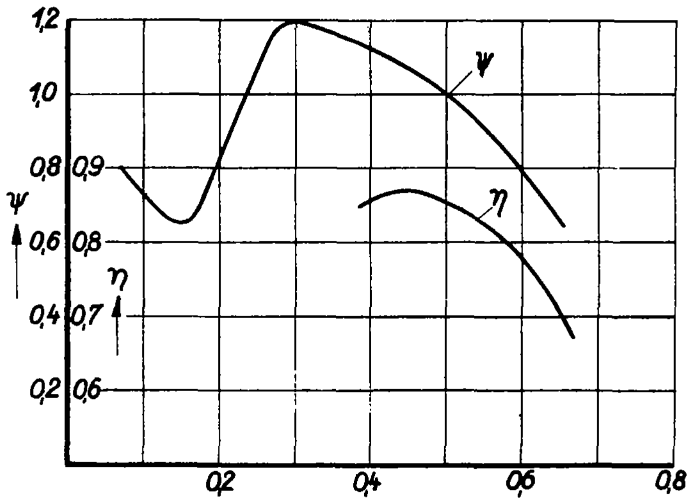


Figure 13.- Test wing for determination of the pressure loss and the feed power requirement. Suction in the flap region, blowing in the aileron region.



$$\varphi = \frac{Q}{F_{Ring}\, u_a}$$

$$\psi = \frac{\Delta p}{\frac{\varrho}{2}\, u_a^2}$$

Figure 14.- Characteristics of the two-stage axial blower. According to ZWB report "Untersuchungen und Mitteilungen Nr. 516" (W. Encke).

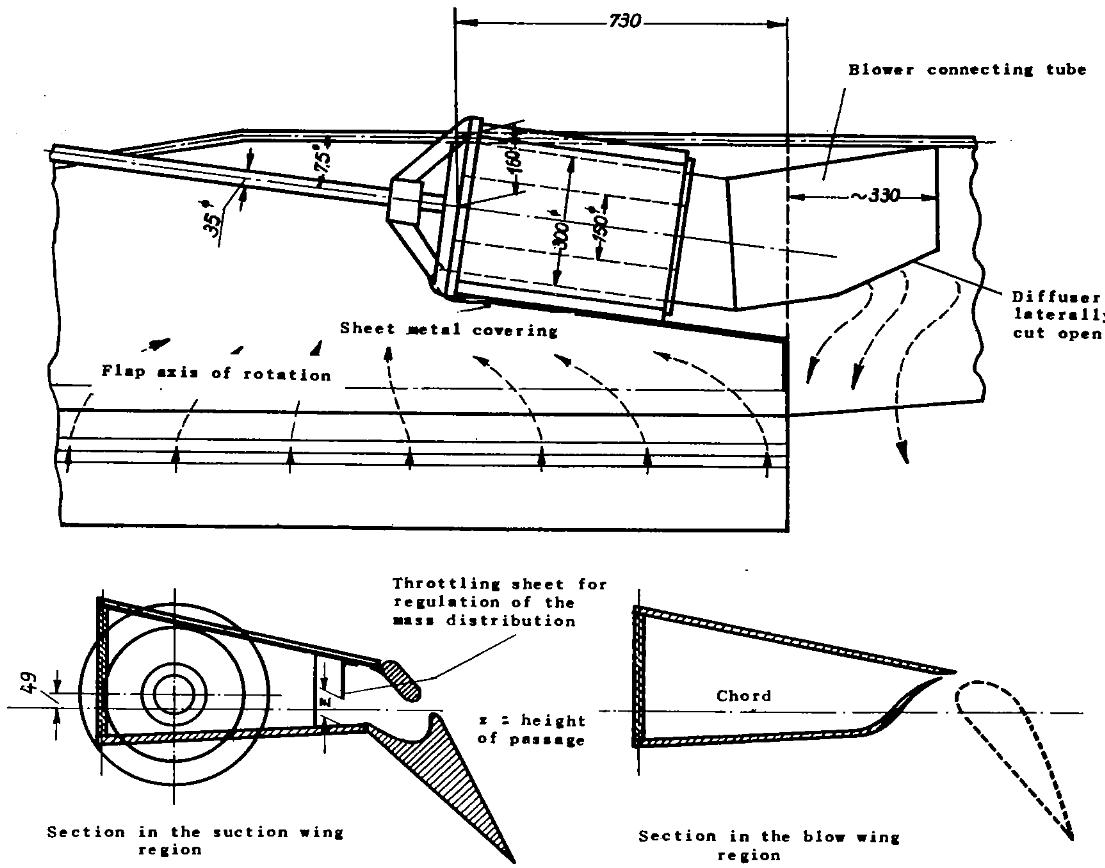


Figure 15.- Blower installation in the test wing.

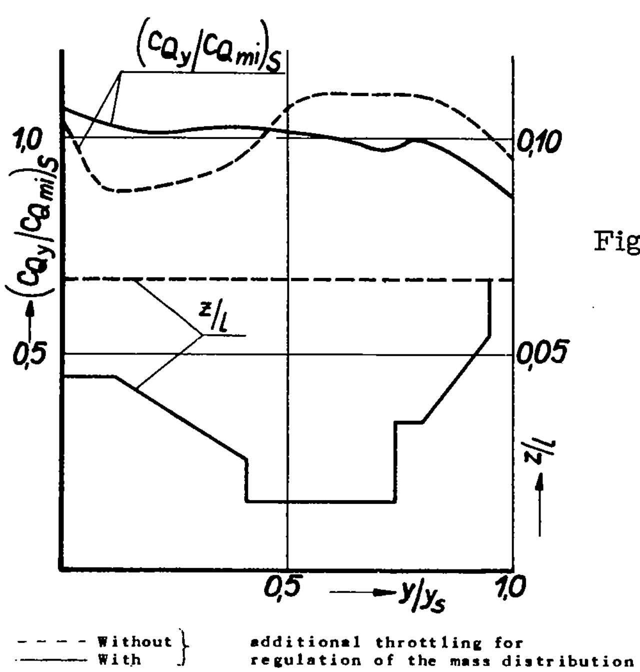


Figure 16.- Distribution of feeding capacity along span of suction part of the wing with and without additional throttling.

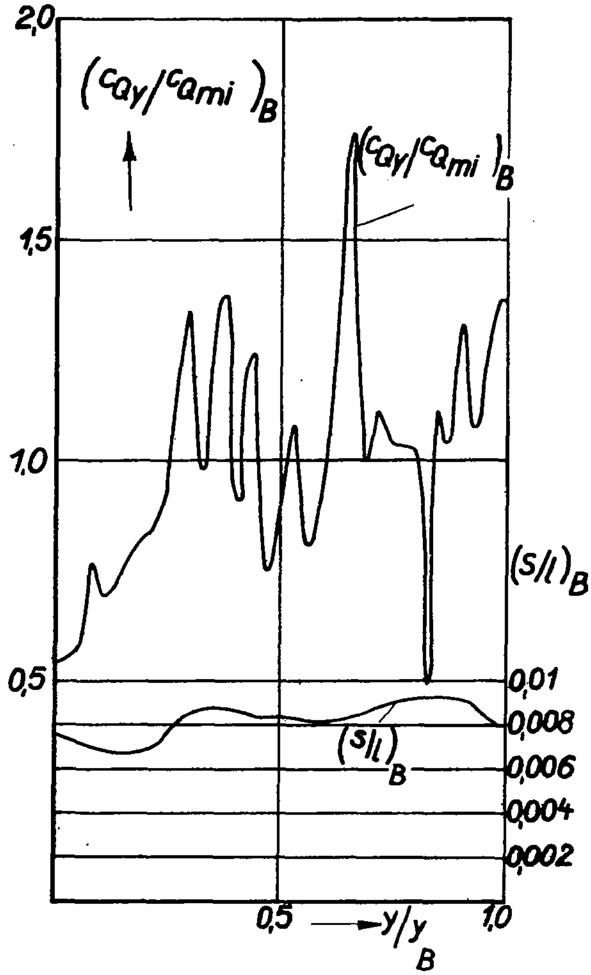


Figure 17.- Distribution of feeding capacity and slot width ratio along span of the blowing part of the wing.

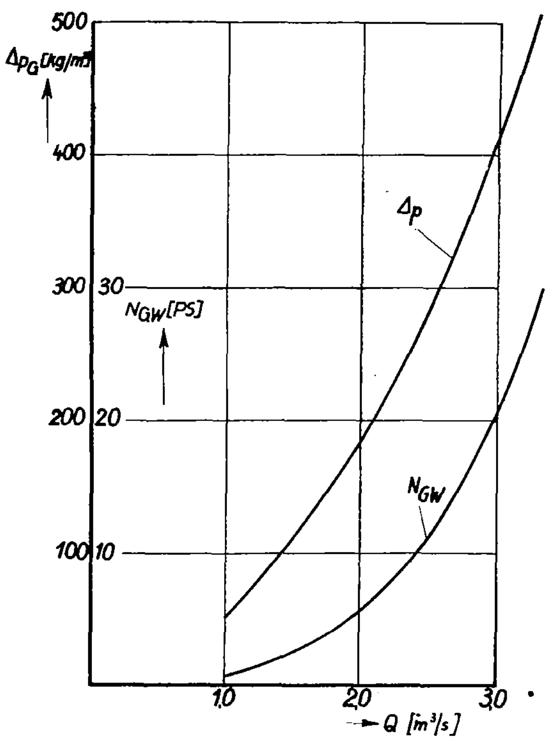


Figure 18.- Test wing of the arrangement I (compound arrangement), connection between feeding capacity, total pressure loss, and power requirement at the blower shaft. Measured at rest (v = 0).

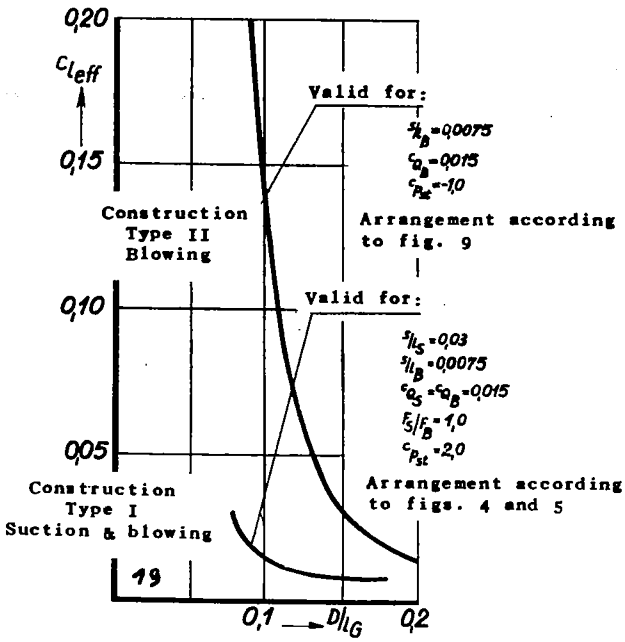


Figure 19.- Effective feed power coefficient $c_{l_{eff}} = \dfrac{75\eta N}{\sqrt{\dfrac{G^3 2}{F_{ae}\rho}}}$ as a function of the ratio "blower diameter/wing chord at the location of the blower" for $c_a = 3.5$. Trapezoidal wing of the aspect ratio 7.5, taper 1:2, hub ratio of the blower $\nu = 0.5$.

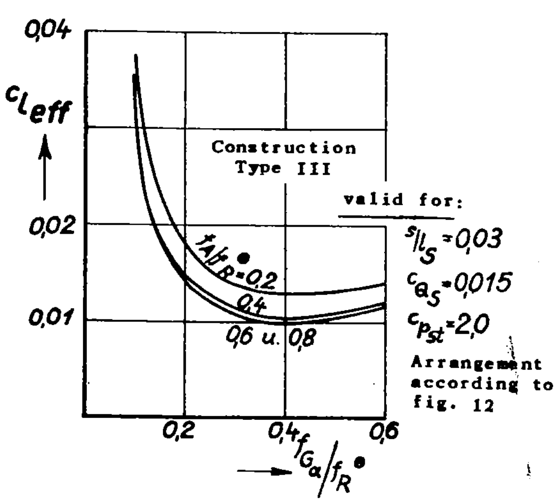
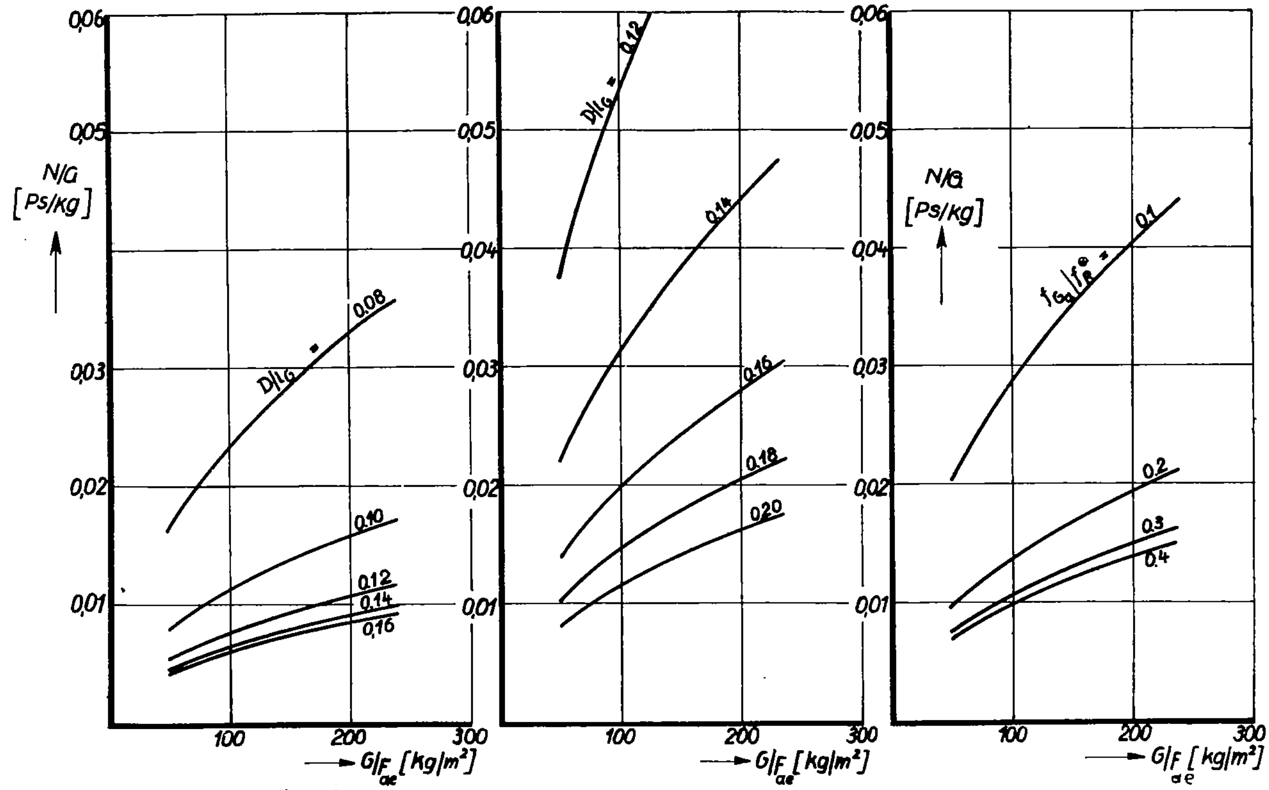


Figure 20.- Effective feed power coefficient as a function of the structural cross section conditions for $c_a = 3.5$, construction type III (suction over the entire span). Trapezoidal wing of the aspect ratio 7.5, taper 1:2, hub ratio of the blower $\nu = 0.5$.



Construction type I
Suction and blowing
(figs. 4 and 5)

$(s/l)_S = 0{,}03$
$(s/l)_B = 0{,}0075$
$F_S/F_B = 1{,}0$
$c_{Pst} = 2{,}0$
$\eta_G = 0{,}7$

Construction type II
Blowing (fig. 9)

$(s/l)_B = 0{,}0075$
$c_{Pst} = 1{,}0$
$\eta_G = 0{,}7$

21

Construction type III
Suction (fig. 12)

$(s/l)_S = 0{,}03$
$f_A/f_R^* = 0{,}20$
$\eta_G = 0{,}7$
$c_{Pst} = 2{,}0$

Figure 21.- Specific feed power requirement $\frac{N}{G}$ PS (German HP)/kg as a function of the surface loading and magnitude of the blower. Example for: $c_a = 3.5$, $c_{Q_S} = c_{Q_B} = 0.015$. Trapezoidal wing, taper 1:2, $\Lambda = 7.5$, hub ratio of the blower $\nu = 0.5$.